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**Intra-Urban Mortality and Air Quality
An Economic Analysis of the Costs
of Pollution Induced Mortality**

Pennsylvania State Univ, University Park

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INTRA-URBAN MORTALITY AND AIR QUALITY:
AN ECONOMIC ANALYSIS OF THE COSTS OF
POLLUTION INDUCED MORTALITY

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FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of these is the Corvallis Environmental Research Laboratory (CERL).

The primary mission of the Corvallis laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects and control of pollutants in lake systems; and the development of predictive models on the movement of pollutants in the biosphere.

This study was initiated by the Washington Environmental Research Center, Office of Research and Development, Washington, D.C. and completed at the CERL, Office of Research and Development, Corvallis, Oregon.

A. F. Bartsch
Director, CERL

ABSTRACT

The possibility that extremely high levels of air pollution can shorten lives and affect the quality of human life was painfully brought to the attention of individuals in the United States by the 1948 episode at Donora, Pennsylvania. Today few people would argue that the existence of pollution concentrations of Donora's magnitude do not have significant health effects. There is substantially less agreement, however, on the significance of the effects of smaller levels of air pollution on health.

This report has attempted to quantify in both physical and monetary terms the effects of existing ambient levels of air pollution on human mortality. A model for the isolation of air pollution's influence on human mortality was developed based on insights derived from existing experimental, episodic, and epidemiological studies. This model was then estimated using weighted linear regression analysis and data from the 1968-1972 experience of Allegheny County, Pennsylvania. The resulting pollution-related mortality functions were then monetized through the use of the most theoretically consistent economic valuation of mortality changes. Specifically, the estimated age-sex-specific pollution-related mortality functions were monetized by applying existing estimates of individual's willingness to pay for mortality decreases.

The results of this study lend support to the contention that an improvement in ambient air quality will produce social benefits in the form of decreased probabilities of death. Specifically, the results obtained for Allegheny County suggest that ceteris paribus efficient resource allocation would be enhanced by devoting relatively more financial resources to the control of particulate matter rather than sulfur dioxide. The validity of this assertion is contingent upon existing technology. Specifically, the present marginal costs of controlling sulfur dioxide exceed the marginal costs of controlling particulate matter; and the estimated mortality benefits of decreasing particulate matter exceed the estimated mortality benefits of decreasing sulfur dioxide. Therefore, on both counts it would appear that relatively more resources should be devoted to the control of particulate matter rather than sulfur dioxide. It must be emphasized, however, that this latter conclusion is based solely on the mortality component of the social benefit function and thus excludes any non-mortality benefits of pollution reduction.

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SECTION I

SUMMARY AND CONCLUSIONS

The motivation for this study was based on the desire to obtain allocational efficiency in the use of the scarce resource clean air. Due to the inherent public good nature of the air resource and the resulting breakdown of the exclusion principle, no market has developed in which property rights could be exchanged. Thus, an optimum allocation of this scarce air resource could not be attained in a private enterprise market economy. Some form of collective or governmental action is required, therefore, to obtain a more efficient allocation of this resource. From an efficiency viewpoint, such governmental intervention should be guided by cost-benefit criteria. This study was designed to facilitate this efficient allocation of clean air by isolating air quality's aggravation effect on intra-urban mortality and then quantifying this portion of the marginal social benefit function in a manner consistent with the theoretical basis of cost-benefit analysis.

The results of this study are of importance to both the theoretician and the public decision maker, since this effort provides a conceptually accurate quantification of the costs of pollution-aggravated mortality. Moreover, the significant policy-relevant contribution of this study is its ability to assist government officials in establishing socially efficient standards for ambient air quality.

While empirical estimates of certain components of the marginal social benefit function have previously been calculated, severe difficulties are encountered when attempting to empirically determine the optimum level of air quality. In particular, the efforts to quantify the marginal social benefit function are greatly complicated by problems of isolating air pollution's many potential effects and evaluating these effects in monetary units. In this study, a regression equation for the isolation of air pollution's influence on human mortality was developed based on insights derived from existing experimental, episodic, and epidemiological studies. The mortality component of the marginal social benefit function was then estimated using weighted linear regression analysis and data from the 1968-1972 experience of Allegheny County, Pennsylvania. The resulting pollution-related mortality functions were then monetized through the use of the most theoretically consistent economic valuation of mortality changes for inclusion in cost-benefit analysis. Specifically, the estimated age-sex-specific pollution-related mortality functions were monetized by applying existing estimates that approximate an individual's willingness to pay for mortality decreases. The weight of the evidence uncovered in this study suggest the following conclusions:

- (1) Both air quality variables, total particulates and sulfur dioxides, exhibit the expected positive relationship to pollution-related mortality. These exacerbating effects while small in absolute terms, are statistically significant for total particulates although statistically insignificant for sulfur dioxide when sulfur dioxide is considered as a separate independent variable.
- (2) The absolute size of the air quality coefficients generally increase with age indicating either that the ability of the body to withstand the influences of total particulates and sulfur dioxide decreases with age, or that there exists a cumulative influence of air quality on mortality. Thus, the distribution of benefits from pollution abatement cannot be isolated by age.
- (3) The absolute size of the air quality coefficients in the pollution-related mortality functions are generally twice as large for males as for females in the less than sixty-five age groups. For the sixty-five and over age group, however, the coefficients are approximately equal for males and females. In essence, this result suggests the possibility of relatively higher exposure levels at work for males compared to exposure levels experienced by females in the residential environment.
- (4) The estimated air pollution coefficients indicate that at the mean, a 1 percent reduction in total particulates will lead to between a 0.23 and a 0.89 percent reduction in pollution-related mortality. It should be recognized that even if the sulfur dioxide coefficients were statistically significant, a similar 1 percent reduction in sulfur dioxide would only result in between a 0.01 and a 0.05 percent reduction in pollution-related mortality. In essence, this result implies a relatively greater importance of total particulates compared to sulfur dioxide.
- (5) Utilizing existing willingness to pay estimates for mortality reductions, it can be concluded that individuals in Allegheny County would be willing to pay a minimum of \$7 million annually in order to maintain total particulates at a level 1 percent below those experienced during the 1968-1972 period. However, for the same period such individuals would be willing to pay only \$0.5 million annually for a similar percentage reduction in sulfur dioxide if the coefficients of sulfur dioxide were statistically significant. Thus, the marginal social benefits accruing to the individuals in Allegheny County from a 1 percent reduction in both of these pollutants exceeds \$7.5 million or the value of the change in the mortality component of the marginal social benefit function.

The results of this study, therefore, lend support to the contention that an improvement in ambient air quality will produce social benefits in the form of decreased probabilities of death. Specifically, the results obtained for Allegheny County suggest that ceteris paribus efficient resource allocation would be enhanced by devoting relatively more financial resources to the control of particulate matter rather than sulfur dioxide. The validity of this assertion is contingent upon existing technology. Specifically, the present marginal costs of controlling sulfur dioxide exceed the marginal costs of controlling particulate matter; and the estimated mortality benefits of decreasing sulfur dioxide. Therefore, on both counts it would appear that relatively more resources should be devoted to the control of particulate matter rather than sulfur dioxide. It must be emphasized, however, that this latter conclusion is based solely on the mortality component of the marginal social benefit function.

The expression of air pollution's aggravation effects on mortality in dollar values consistent with the other components of cost-benefit analysis will, however, facilitate the efficient allocation of society's scarce resource clean air. By monetizing the mortality component of the marginal social benefit function, more enlightened decisions about the socially optimum level of air quality can be formulated. In essence, these dollar estimates will allow decision makers to more closely approximate the optimum level of air quality by permitting the direct comparison of mortality reduction and other benefits of air pollution abatement with the costs associated with the various abatement policies.

Further research is, however, required to test the reliability of both the mortality functions and willingness to pay estimates. For example, it is not completely clear whether the relatively large influence of particulate matter on mortality is due to the specific elements of which it is composed in Allegheny County or the inherent characteristics of particulate matter. Thus any extrapolation of these results to other geographic areas must be made with extreme caution. Additional research is also needed on individuals' willingness to pay for mortality decreases including the valuation of family, friends and society and the other components of the marginal social benefit function.

Changing lifestyles and increased population have forced man to recognize that the assimilative capacity of his natural environment is indeed limited. Hence, environmental preservation possesses a long-term problem of resource allocation and as such the environment must be efficiently managed. Public decision makers as well as the general public should begin taking affirmative action to control environmental degradation. It is hoped that this study has contributed to both an increased understanding of the impacts of air pollution as well as stimulated the efficient use of society's scarce resource clean air.

SECTION II

RESOURCE ALLOCATION AND AIR POLLUTION

INTRODUCTION

Since his appearance on earth, man's pursuit of well-being, and in fact his very existence, has been a source of pollution. Historically, nature has been capable of absorbing man's organic and inorganic waste with little difficulty.¹ Despite isolated instances, it was not until the twentieth century that pollution was considered more than simply an annoyance.

The emerging concern about environmental degradation has been prompted by a combination of recent developments. As world population grew larger in size and affluence, so did society's wastes. New and exotic goods created by technology put even more of a burden on nature's recycling capabilities since many of the new products were not readily biodegradable.² Moreover, increased leisure time resulting from greater affluence enabled man to enjoy what was left of his once pristine environment. Through experience and the mass communication media, society became aware of incidents in which the health and well-being of large numbers of people were affected by their increasingly polluted environment. The 1948 episode at Donora, Pennsylvania,³ the 1962 London fog,⁴ and the almost daily smog surrounding Los Angeles became topics of conversation, concern and controversy.

Man has now been forced to recognize that nature's assimilative capacity is indeed constrained and, consequently, clean air and water are scarce resources. The abatement of pollution requires, either explicitly (in terms of pollution control methods) or implicitly (in terms of foregone output) the utilization of scarce resources that have alternative uses. In essence, the decision on the degree of abatement thus becomes an economic problem of maximizing the net gain associated with changes in environmental quality. If man desires to improve his well-being, he must begin applying to the use of air and water the same efficiency criteria that economists have traditionally applied to the allocation of other scarce goods. One point remains certain:

. . . we have to go on using the environment . . . (man's) activities cannot be abolished, though they can be controlled. Controlling them means finding the proper balance between the utility of these activities to the individual and the disutility they impose, via the environment, on others.⁵

Although this report is primarily intended to make a contribution toward the efficient allocation of the scarce resource clean air, the results will nonetheless be applicable to the allocative decisions concerning other environmental goods.

EFFICIENT USE OF RESOURCES

Any analysis designed to evaluate alternative allocation schemes for a scarce resource must be an exercise in applied welfare economics. As such, the analyst must recognize that alternative distribution schemes "differ with respect to both efficiency and equity"⁶. Therefore, the alternatives must be evaluated in terms of both efficiency and equity considerations.

Equity considerations involve normative judgments which are generally recognized as outside the appropriate realm of the economist as an economist. Analysis of changes in the distribution of wealth which result from changes in allocative procedures, however, should not be ignored by the economist. (Such distribution aspects will be discussed in Section V.⁷) Evaluation of the relative efficiency of alternative allocation schemes is, however, the forte of economists. It is traditional for economists to assess an optimal organization of economic activity in terms of efficiency. In general, an economy is said to be optimally organized when "it is not possible, by any reallocation of factors, to make anyone better off without making at least one person worse off".⁸ Any situation which fulfills this criteria is said to be a "Pareto Optimum," "Pareto Efficient" or simply "Efficient" position for society.

Before any progress can be made toward the efficient allocation of the scarce resource clean air, one must initially consider the general efficiency criteria and the reasons why such criteria have not traditionally been applied to this resource in man's quest for well-being. The conditions necessary for the attainment of a Pareto optimum can be stated in terms of either consumption, production or more generally, as a combination of both. In the general case the necessary condition requires that equality exist between the marginal rates of substitution in consumption (MRS) between any two goods (e.g., a and b),⁹ and the marginal rates of transformation in production (MRT) between the same two goods.¹⁰ This condition can be expressed as:

$$MRS_{ab} = MRT_{ab}$$

(1)

One of the more engrossing insights gained by a closer inspection of this marginal condition is that a society characterized by perfectly competitive markets in which all costs and benefits are transacted will allocate its resources in a Pareto efficient manner provided that certain technological and motivational assumptions are fulfilled.¹¹ Indeed, this is the modern reasoning behind Adam Smith's famous statement:

. . . every individual necessarily labours to render the annual revenue of the society as great as he can. He generally, indeed, neither intends to promote the public interest, nor knows how much he is promoting it. By preferring the support of domestic to that of foreign industry, he intends only his own security; and by directing that industry in such a manner as its produce may be of the greatest value, he intends only his own gain, and he is in this, as in many other cases, led by an invisible hand to promote an end which was no part of

his intention. Nor is it always the worse for the society that it was no part of it. By pursuing his own interest he frequently promotes that of the society more effectually than when he really intends to promote it.¹²

The implications of this result for the problem under consideration in this study are quite significant, especially at the theoretical level. In effect, this result suggests that if the necessary relationships hold in all markets except the market for clean air, then the welfare of society might be improved to the maximization point without making any individual worse off. Unfortunately, "(few) markets in our economy are perfectly competitive, because few markets fulfill the conditions of perfect competition"¹³. Indeed, as will be illustrated later, one of the primary problems associated with the allocation of the scarce resource clean air is the absence of a market for this resource due primarily to the high transaction costs involved in establishing such a market.

What then is the purpose of basing policy recommendations for welfare improvement on implications derived from the perfectly competitive model? The primary virtue of this model is that if its assumptions are met "it provides a standard of efficiency by which actual economic institutions and organizations can be appraised"¹⁴. Thus, by basing the analysis on a comparison of the existing economic situation with what might be attained in the perfectly competitive model, insight into corrective policy measures can be formulated. This is the procedure to be followed in this study since it enables policy makers, if they so choose, to more closely approximate the results of an optimal (perfectly competitive) market situation and thereby, hopefully lead to improvement in society's welfare.

EXTERNALITIES, TRANSACTION COSTS AND PUBLIC GOODS

Abstracting from the problem of obtaining the necessary conditions for perfect competition, allocation problems can still arise due to "Pareto-relevant" externalities which preclude the attainment of welfare maximization.¹⁵ The problems which arise because of such externalities are the primary reason why even under perfect competition, efficient utilization of such resources will not result from the free interaction of market forces. As Pigou notes:

. . . we may set out first a number of instances in which marginal private net product falls short of marginal social net product, because incidental services are performed to third parties from whom it is technically difficult to extract payment . . . It is true of resources devoted to the prevention of smoke from factory chimneys: for this smoke in large towns inflicts a heavy uncharged loss on the community, in injury to buildings and vegetables, expenses for washing clothes and cleaning rooms, expenses for the provision of extra artificial light, and in many other ways.¹⁶

Pigou's statement implies that externalities cause our marginal equality condition for the attainment of efficient resource allocation to be violated

and thus become an inequality. This result can be visualized by recognizing that the MRT_{ab} is simply equal to the ratio of the marginal costs of a and b. As stated earlier, the MRT_{ab} included both private and social costs:¹⁷

$$MRT_{ab} = MC_a / MC_b \quad (2)$$

In the case of externalities in the production of a, the marginal private costs (MPC) no longer equal the marginal social costs (MSC):

$$MPC_a / MPC_b = MSC_a / MSC_b \quad (3)$$

In effect, this latter relationship implies, given the basis of our efficiency criteria, either too much of some goods and services or too little of certain other goods and services are being produced, prohibiting the attainment of maximum social welfare. In order to alleviate this situation, some method must be employed to equate private costs to social costs. Ideally, from an efficiency viewpoint, these costs and benefits should be directly included in the individual's or firm's decision-making process. In this way, all costs and benefits (private and social) would be internalized and society could conceivably attain a Pareto efficient position. Coase has provided one of the earliest and most significant treatments of this internalization process. He has demonstrated that optimum resource allocation will result if the party imposing the externality and the party receiving the externality are able to negotiate at zero costs.¹⁸ The key qualification to recognize is "at zero costs," because:

Once the costs of carrying out market transactions are taken into account it is clear that such a rearrangement of rights will only be undertaken when the increase in value of production consequent upon the rearrangement is greater than the costs which would be involved in bringing it about.¹⁹

Indeed, it can be argued that market failure in the case of allocation of pollution rights and other externalities "is the particular case where transactions costs are so high that the existence of the market is no longer worthwhile".²⁰

The primary reason for these prohibitively high transaction costs is that no individual may be excluded from the consumption of clean air. Thus, the exclusion principle becomes inapplicable and precludes transactions at any cost. Hence, no individual can be relied upon to reveal his preference since he knows that he will benefit from the corrective actions of others. Therefore, an individual can enjoy a "free ride" at society's expense, while incurring zero private costs. This problem while inherent to varying degrees in all public goods, is especially relevant to air. In essence, this resource is a classic example of a pure public good in that "each individual's consumption of such a good leads to no subtraction from any other individual's consumption of that good".²¹ Hardin demonstrates the resulting allocation problems of communal resources in his example of common grazing land:

. . . the conclusion reached by each and every rational

herdsman sharing a commons . . . [is] that the only sensible course for him to pursue is to add another animal to his herd. And another; and another Therein is the tragedy. Each man is locked into a system that compels him to increase his herd without limit--in a world that is limited.²²

Recognizing that no individual may be excluded from the consumption of ambient air, determinization of the socially efficient level of air quality must consider each individual's MRS. Thus, the pervasive nature of public goods requires the modification of the simple efficiency criteria presented earlier. Since all individuals may potentially consume equal quantities of pure public goods, the relevant efficiency criteria must equate the summation of their MRS with the MRT.²³

STATEMENT OF THE PROBLEM

From the preceding discussion it is apparent that an optimum allocation of the scarce resource clean air cannot be attained in a private enterprise market economy. In other words, social welfare cannot be maximized via the free interaction of market forces because of the prohibitively high transaction costs associated with overcoming the breakdown of the exclusion principle. The only viable alternative to the free interaction of market forces appears to be some form of collective or governmental action. Indeed, as Buchanan notes "a basic reason for political or government action . . . [is] reduction in transaction costs where benefits can only be secured from large-number exchanges".²⁴ This reduction in transaction costs can be attributed to state intervention because the state "by its nature, . . . has a monopoly of coercive power and coercive power can be used to economize on transaction costs".²⁵

Specifically, this report is designed to facilitate the efficient allocation of our scarce resource clean air by isolating air quality's aggravation effect on intra-urban mortality and then quantifying these costs in a manner consistent with the theoretical basis of cost-benefit analysis. The results from this study will be of importance to both the theoretician and the public decision-maker, since this effort provides a conceptually accurate quantification of the costs of pollution aggravated mortality. Moreover, the significant policy-relevant contribution of this report will be to assist government officials in establishing socially efficient standards for ambient air quality.

The following section will develop an econometric model designed to isolate the aggregation effect of long-term low-level dosages of air pollution on individuals. This model will then be used to quantify the pollution-mortality relationship for Allegheny County, Pennsylvania in Section IV. Section V will trace the development of criteria that can be used as a guide for the suggested collective action in the quest for efficient allocation of the scarce resource clean air. Section VI addresses the issue of assigning dollar values to air pollution-induced mortality in a manner consistent with the guidelines developed in Section V and then applies existing empirically estimated results to the pollution-mortality results obtained earlier for Allegheny County.

SECTION III

AIR QUALITY AND MORTALITY: DEVELOPMENT OF THE MODEL

The objective of this section is to develop an appropriate model for empirically estimating the aggravation effects of ambient air quality on mortality. This model will then be used for later quantification of these effects in both absolute and dollar units. The model developed in this section is based on insights derived from existing experimental, episodic, and epidemiological studies.

PREVIOUS STUDIES, INSIGHTS AND PROBLEMS

The possibility that extremely high levels of air pollution can shorten lives and affect the overall quality of human life was painfully brought to public attention by the 1948 episode at Donora, Pennsylvania.²⁶ Today few people would argue that the existence of pollution concentrations such as were present during the Donora episode do not have significant health effects. There is substantially less agreement, however, on the significance of lower levels of air pollution on health.

The existence of these potential health effects has received increased attention in recent years. A growing number of experimental episodic, and epidemiological studies have shown inverse relationships between air quality and various measures of health. Although the entire spectrum of potential health effects on humans have been studied, "mortality is currently the best documented and defined health indicator available".²⁷ Therefore, this study will use the insights derived from these earlier works in an attempt to develop a model capable of estimating the relationship between ambient air quality and mortality differentials.

Experimental Studies

Any attempt to isolate air quality's impact on human mortality must initially recognize that air quality is only one of numerous factors which influence an individual's probability of death;²⁸ therefore, these other factors must be held constant experimentally or controlled statistically.

While the list of potentially dangerous atmospheric contaminants increases annually, the current effort concentrates on sulfur oxides and particulate matter since these are two of the most pervasive stationary source contaminants found in the atmosphere. The responses of several animal species, including man, to sulfur oxides and particulate matter have been studied using various experimental techniques. Although such experimental studies have shown changes in vital functions and mortality in animals, only changes in selected functions

(primarily pulmonary) could be studied in man due to legal and ethical considerations.

The majority of clinical experiments on animals have demonstrated that sulfur oxides, usually sulfur dioxide or sulfuric acid, irritate the respiratory system.²⁹ In an attempt to induce animal mortality from such contaminants, however, these studies required concentration far in excess of those doses likely to be found even in extremely polluted areas. As the U.S. Department of Health, Education and Welfare (USHEW) notes:

Compared to realistic air pollutant levels, it requires relatively high concentrations of sulfur dioxide or sulfuric acid to produce pathological lung change or mortality in animals.³⁰

Particulate matter unlike sulfur dioxide or sulfuric acid, is composed of a variety of substances, many of which are known to be toxic (e.g., asbestos, beryllium and lead). Since most of these contaminants are primarily area specific, an evaluation of the effects of each of these individual substances is outside the scope of this study.³¹ The current effort focuses on "general" particulate matter of the type usually monitored by high-volume samplers. Experimental investigations have demonstrated three ways in which particulate matter may exert toxic effects:

1. The particle may be intrinsically toxic due to its inherent chemical and/or physical characteristics.
2. The particulate may interfere with one or more of the clearance mechanisms in the respiratory tract.
3. The particle may act as a carrier of an absorbed toxic substance.³²

Some experimental studies with animals have also demonstrated the existence of synergistic effects of various types of particulates and sulfur oxides. Busbtueva (1957, 1962) has shown that the exposure of guinea pigs to a 0.5 mg/m³ sulfuric acid produced only slight lung irritation, although when combined with 0.9 mg/m³ sulfur dioxide considerable changes in lung pathology resulted. Other experiments (Gross, *et al.*, 1967) have also indicated that normally inert particles (e.g., carbon) can be made irritant when combined with sulfur dioxide or nitrogen dioxide. Toyama (1962), for example, has demonstrated the existence of similar synergistic effects with sulfur dioxide and sodium chloride. Experiments involving humans, however, are much harder to interpret due to the variability of responses between different individuals and the same individuals at different times.³³ This fact, combined with the high levels of exposure required to induce mortality in clinical animals, has resulted in qualitative inferences about air quality rather than quantitative estimates concerning the effects of ambient air quality on human mortality.

Episodic Studies

Analysis of actual extreme exposure episodes provides one method of overcoming the many technical, legal and ethical constraints associated with experimental studies. In essence, by utilizing real-life experience, information can be obtained on human mortality changes associated with extremely high levels of air quality. In fact, most episodic studies (Schrenk, et al., 1949; Wilkins, 1954; Scott, 1963; Riggan, et al., 1976) have confirmed the existence of a direct positive relationship between high levels of air pollution and mortality. When the 1948 episode of Donora, Pennsylvania was analyzed, Schrenk, et al., (1949) discovered that most of the twenty individuals who died during the episode had previously existing cardiovascular or respiratory diseases. Therefore, while quantification of air quality's influence on mortality was not possible due to insufficient air quality data, insights were attained concerning the illnesses likely to be exacerbated by air pollution.

Wilkins (1954) estimated that the December 1952 London fog resulted in approximately 3,500 to 4,000 excess deaths. The most frequent causes of death listed during this episode were chronic bronchitis, bronchial pneumonia, and heart disease. Similar, although not so drastic results ("only" 700 excess deaths) were obtained by Scott (1963) for the three day 1962 London episode. While measurements of air quality (e.g., smoke and sulfur dioxide) were available for both of these episodes, such data were not detailed enough to attempt quantification of a dose-response function.

The most recent air pollution episode, the 1976 Pittsburgh experience, was analyzed by Riggan, et al. After adjusting for incomplete death records,³⁴ days of the week, temperature, precipitation, and season, researchers still determined that at least fourteen excess deaths occurred during the period.

Although episodic studies have the advantage of being able to study human mortality, such studies are limited in usefulness since they deal only with specific episodes of abnormally high pollution. Therefore, episodic investigations are not applicable to the everyday ambient levels of pollution faced by individuals in urban areas and any extrapolation of dose-response functions from these episodes must be considered tenuous at best. As Anderson notes:

Although the deleterious effects of acute exposures to air pollution are well established, it is not possible to extrapolate from these data to the low levels of air pollution to which persons are exposed in a modern urban society.³⁵

Analyzing changing patterns of human mortality that occur during high exposure episodes, however, can provide insights into which illnesses are most likely to be exacerbated by air pollution at the lower, more typical levels to which individuals are exposed daily.

Epidemiological Studies

The limitations of episodic and experimental research have resulted in the increased use of epidemiological studies to isolate the effects of ambient levels of pollution on mortality. Epidemiological studies analyze the effects of pollution at typical, rather than abnormally high, levels of exposure. Moreover, individuals are studied in their everyday environment and not in a laboratory, thus adding to the attractiveness of employing such studies. Indeed, as USHEW notes "other countries, notably the Netherlands and Sweden, have based their air quality criteria solely on epidemiological studies".³⁶

Results from most epidemiological studies have also shown an inverse relationship between air quality and mortality. The procedure used in these studies typically involves simply calculating different mortality rates (or partial correlation coefficients for populations exposed to different air quality conditions. These studies have typically controlled for socioeconomic variables which influence an individual's probability of death by dividing the population of the area under study into four or five socioeconomic groups.³⁷ The difficulty with using these types of statistical control techniques is that there exists many other factors correlated with air pollution that affect human mortality and are not adequately controlled for by the use of partial correlation coefficients. Freeman (1972), for example, has shown that air quality levels of white neighborhoods are higher than those of non-white neighborhoods. In addition, individuals with relatively high income and education levels also tend to reside in less populated areas of relatively better air quality, while the lower income and less educated classes tend to be constrained to the more polluted, crowded sections of the city. Since income, educational levels, and population density all influence mortality, these relationships cause difficulty in isolating air quality's influence on mortality through the use of simple correlation techniques. Indeed, as Lave and Seskin note:

If the explanatory variables were orthogonal to each other, the inability to get measures on all variables would not be important. If they were dependent, one could find the effect of any variable on the mortality rate by an univariate regression. However, orthogonality is not a reasonable assumption This collinearity among explanatory variables means that univariate regression, or simple cross tabulations (which constitutes the preponderance of evidence), are not likely to produce results that one would interpret.³⁸

In an attempt to circumvent these limitations, Lave and Seskin estimated their own relationships using mortality data for 117 Standard Metropolitan Statistical Areas (SMSA's) for the period 1959-1961. Their study used multiple regression analysis to explain the variance in thirty-four different mortality rates (characterized by age: under twenty-eight days, under one year, fourteen years and younger, fifteen to forty-four, forty-five to sixty-four, and sixty-five and older; race, white, and non-white; and sex, male and female). The independent variables specified by Lave and Seskin were minimum sulfates, mean particulates, minimum particulates, percent poor, population

per square mile, percent of population sixty-five or older, percent non-white. It should be recognized that only some of these variables appear in any of their specific linear regressions since only the "best" results were publically presented. As illustrated in Table 1, the results of their linear regressions demonstrate a predominantly direct relationship between levels of pollution and mortality. The sole exception to the expected positive relationship was the negative coefficients of minimum sulfates for the white population in the fifteen to forty-four age group. This result combined with the generally increased magnitude of the pollution coefficients with age suggests that: (1) individuals in this age group die primarily from non-pollution related causes; (2) the ability of the body to withstand the influence of pollution decreases with age; or (3) there exists a cumulative effect of pollution on human mortality.

Another interesting insight attained from a careful examination of Table 1 is that the effect of particulates is greater on white males than white females in the less than sixty-five age groups. This result suggests the possibility of relatively higher exposure level for white males as a result of work-related experience.

The generally larger coefficients for the non-white population relative to the white population may indicate actual racial differentials in response to air pollution. Alternatively, the larger coefficient for non-whites may result from the fact that non-whites tend to reside in more heavily polluted areas (implying a non-linear dose-response curve), are generally less educated and earn lower incomes than the white population. Unfortunately, it is impossible to determine which, if any, of these relationships is appropriate due to data limitations experienced by Lave and Seskin.

While attempts at rationalizing the racial differences in the coefficients highlight the difficulties arising from data limitations, the restrictions imposed on Lave and Seskin's analysis by such constraints are far more pervasive. The most important of their data limitations was the use of only one monitoring station's readings for an entire SMSA in order to measure ambient air quality. As they readily acknowledge, "it is a heroic assumption to regard these figures as representative of an entire SMSA in making comparisons across areas".³⁹ It is also possible that the inaccuracy of their mortality rate calculations compound the difficulties of interpreting their results. As Lave and Seskin recognize:

These age specific death rates were derived by dividing the number of people who died by the total population. If the age distribution of people differs across cities, these approximate death rates will not even be proportional to the true rates.⁴⁰

Errors in the measurement of these dependent variables could also be a reason for the relatively low coefficients of determination for their disaggregated (age-sex-specific) mortality rates.⁴¹

In an attempt to determine if their results had isolated a true relationship between ambient air pollution and mortality and not a relationship caused

TABLE 1. SUMMARY OF LAVE AND SESKIN INTER-URBAN MORTALITY FUNCTIONS*,†

	15-44		45-64		65 and Over	
	Male	Female	Male	Female	Male	Female
PART A. WHITE OVERALL MORTALITY						
R ²	.236	.164	.336	.395	.385	.295
Constant	52.921	28.626	45.138	131.695	698.367	470.984
Mean particulates	.036	.026	.127	.086	-	-
Minimum sulfates	-.021	-.005	.069	.185	.637	.806
Population per square mile	.000	.001	.006	.003	-	-
Percent of population non-white	-.023	-.013	.107	-.028	-	-
Percent of population over 65	-.062	-.025	.202	.065	-	-
Percentage of poor	.069	.023	.154	-.009	-	-
PART B. NON-WHITE OVERALL MORTALITY						
R ²	.321	.345	.311	.477	.051	.108
Constant	49.719	30.009	237.856	141.855	679.310	499.750
Mean particulates	.150	.111	.252	.373	-	-
Minimum sulfates	.028	.068	.099	.980	.927	.904
Population per square mile	.003	.001	.006	-.004	-	-
Percentages of population non-white	.140	.104	.326	.472	-.066	-.066
Percentage of population over 65	.033	.054	.406	-.109	-	-
Percentage of poor	.180	.110	.667	.333	-	-

*Source: Lave and Seskin (1970b).

†All mortality rates (dependent variables) are in deaths per 10,000.

by meteorological differentials or personal pollution from home heating sources, Lave and Seskin (1972) added various climatic and home heating variables (e.g., humidity, temperature, and various types of home heating equipment) to their model. This analysis while also based on 117 SMSA's was not age-sex-specific since only total and infant mortality functions were estimated.⁴² The inclusion of these additional variables did not alter the positive nature of the association between air pollution and mortality nor the stability of the air quality coefficients.

In general neither climate nor home heating variables cause the air pollution variables to lose significance. While there are individual pollution coefficients which do lose significance, the coefficients are quite stable. An exception occurs when home heating fuels are added. These variables are associated closely with measured air pollution and both pollution and heating fuel variables tend to become insignificant. . . . Apparently, the type of fuel used for home heating is a major contributor to the air pollution level in the city. Note that this interpretation does not mean that the previous association between air pollution and mortality is disproved, but rather it is made more specific by directing the association to home heating fuels, rather than at all sources of air pollution.⁴³

The use of simple total mortality figures instead of an age-standardized total mortality ratio could introduce some biases (e.g., higher or lower estimates of the effects of air quality) into the analysis,⁴⁴ especially if the age distribution of the SMSA's varies with their air quality.⁴⁵

Even with these limitations, Lave and Seskin have significantly advanced our insights into the epidemiological association between ambient air quality and mortality. Specifically, their studies have demonstrated that, after controlling for other factors which may affect mortality, air quality does exhibit a significant relationship with mortality. Experimentation with alternative specifications (i.e., functional forms) have given results not significantly different from the general linear model depicted in Table 1.

The first of these involved a comparison of the linear model with a log-linear specification. It was found that the elasticities associated with the pollution variables . . . [in the linear model] were quite similar to the coefficients of the pollution variables in the log-linear formulation. When a quadratic model was fit . . . (squared values of the pollution variables as well as an interaction term), the results of an F-test indicated that the gain in explanatory power was insignificant.⁴⁶

Whether these associations are causal is still an unsettled issue. However, the experimental and episodic works previously discussed strengthen arguments for at least the existence of an aggravation effect.

Recognizing the probable existence of this aggravation effect, the next section will detail a generalized model developed from the insights of earlier studies, which is capable of isolating such effects. Specific attention will be given to demographic considerations, initial variable selection and overcoming the technical, legal, ethical and data problems associated with previous attempts at isolating the relationship between air quality and mortality.

THE MODEL

This section describes a general model that isolates the effects of various factors affecting mortality differentials and explains the candidate variables. The model is designed for application to a specific urban area, and thus avoids many of the difficulties encountered by other investigators (primarily Lave and Seskin) who analyzed inter-urban mortality differentials. Although specifically designed for intra-urban analysis, the model is also applicable to analyzing inter-urban mortality differentials.

Dependent Variables

Any attempt to provide a reliable estimate of the effects of air quality on mortality via intra-urban mortality analysis must recognize that other factors, many of which are collinear to air quality, influence the risks of death. Therefore, in order to isolate the affect of ambient air quality on mortality, it is necessary that these other factors be controlled. The first of these factors to be controlled for will be the demographic influences. Such components are most readily controlled through the use of age-sex-race-specific mortality rates.

In general, children are not subject to the same hazards as adults. This observation, coupled with a decreasing ability of the body to protect itself after a certain age, leads to the expectation of mortality differentials with respect to age. In fact, there exists an inverse relationship between age and mortality after early infancy.

Differentials in risk of death can also be expected on the basis of sex. Whether or not these differentials are biological or social is still an unsettled question, although females do enjoy more favorable mortality rates.

Differential mortality is also exhibited by different races within any sex-age group. With the exception of those causes of death related to inherent genetic deficiencies such as sickle cell anemia, this may result from social class differences. Despite lack of clear understanding of the real causal factors, the significance of racial differences in mortality is sufficient reason to control, at least initially, for race when analyzing the effect of air quality differentials on mortality.

Finally, it must be recognized that air quality can be expected to accentuate the risks of death from certain causes (e.g., bronchitis, emphysema, asthma, etc.). Therefore, deaths should be separated into various causes to enable the isolation of those types which are most likely to be influenced by various levels of air quality. Thus, by controlling for

age, sex and race as well as examining cause-specific mortality rates, it is possible to partially isolate the effects of air quality on mortality from those other influences. Toward this objective, age-sex-race-cause-specific mortality rates will be used as the dependent variables in the multiple regression analysis. Another advantage of using these specific mortality rates (particularly age and sex) as dependent variables is that such variables provide valuable indicators of the primary etiological effects of air pollution. Specifically, isolating preschool and school-aged children and, to a lesser extent housewives, avoids the complications of exposure to pollutants at work.⁴⁷

Independent Variables

The existence of important factors in addition to age, sex, race and air quality that may be collinear to other independent variables and also influence an individual's risk of death justifies the use of multiple regression analysis. These factors include income, education, social class, occupation, place of residence, housing, climate, availability and access to quality medical care, quantity and quality of food consumed, tobacco consumption, sanitation and marital status (Kosa, et al., 1969, Shryock and Siegel, 1971). Unfortunately, measurement or observation of many of these factors is extremely difficult, if not totally impossible. Certain proxies and estimates, however, can be used in the absence of direct measurement. The following independent variables will be considered in the initial model:

Income (Y)

In general, individuals with higher incomes tend to consume higher quality goods which should favorably affect their health. A negative association between income or some other proxy for social class has been demonstrated by many investigators researching class differentials in mortality (Chapin, 1924; Mayer and Hauser, 1950; Yeracaris, 1955; Ellis, 1957, Kitagawa and Hauser, 1968; Roberts, et al., 1970). Fuchs (1965, 1973) and others (e.g., Auster, et al., 1969), however, have shown that after controlling for other factors (e.g., education), income does not indicate a significant negative relationship and may even exhibit a positive relationship. In this analysis, therefore, income will be used primarily as a proxy for unmeasured socioeconomic variables.

Education (E)

"Higher levels of education may be associated with relatively more medical care at preventive stages".⁴⁸ Moreover, education levels may also be associated with the possession of better knowledge of preventive care and willingness to seek and follow a doctor's advice. Negative associations between education and mortality have been found by Kitagawa and Hauser (1968), Fuchs (1965, 1973) and Auster, et al., (1969).

Cigarette Consumption (C)

The deleterious effects of cigarette consumption have been brought to the public's attention primarily by the U.S. Government (U.S. Department of Health, Education and Welfare, 1964, 1969c). Positive associations between cigarette consumption and mortality have been demonstrated by Auster, et al., (1969) and Fuchs (1968).

Health Insurance (I)

It is generally believed that the possession of health insurance may have a significant effect on an individual's decision to seek medical care. Feldstein (1971, 1973) and Rosett and Huang (1973) have empirically demonstrated this possibility. Therefore, differences in the incidence of health insurance will account for a portion of the variance in mortality rates.

Population Density (PD)

Proximity to other individuals can influence one's exposure to various diseases. Lave and Seskin (1970a, 1970b, 1972 and 1973) have been shown a significantly positive relationship between population per square mile and inter-SMSA differentials in mortality.

Total Particulates (TP), Dustfall (D), Sulfur Dioxide (SO₂), and Suspended Sulfates (SS)

These proxies are the most commonly used air quality measures and should be considered as the air quality variables. Total particulates and/or dustfall should be considered because of the belief that they are "the most important constituent"⁴⁹ of air quality's influence on health due to their almost universal presence and relative magnitude. Sulfur dioxide should be considered due to its use in the laboratory studies mentioned earlier (Bustueva, 1957, 1962; Gross, *et al.*, 1967 and Toyama, 1962) and also to test for possible synergistic effects with total particulates and/or dustfall. Suspended sulfates should also be examined for their possible long-run effects since recent Community Health and Environmental Surveillance System (CHESS)⁵⁰ studies indicate that health effects of short-term exposures to air pollution "should be attributed to suspended sulfate levels rather than to observed concentration of those [sulfur dioxide or total particulates] pollutants".⁵¹

Average Annual Temperature (TEMP), Average Annual Daily Maximum Temperature (DMAX), Average Annual Daily Minimum Temperature (DMIN), Number of Degree Days (DDAYS), Total Amount Precipitation (TPRE), Number of Days with Maximum Temperature 90° or Greater (#90+), Number of Days with Maximum Temperature 32° or Less (#32-), the Number of Days with 0.1 Inches or More Precipitation (#P.1+) and Relative Humidity (RHUM)

These are the most readily available climatological variables. Although climate has been recognized as an important factor in mortality (Hirsch, 1941; Peterson, 1947; Berke and Wilson, 1951), the literature on the cause-effect mechanism has not been developed to the stage where it can determine which climatological variables are of major importance. This reason, together with data availability, is responsible for the selection of these plausible explanatory climatological variables. It should also be noted that these nine variables were among the fourteen originally considered by Lave and Seskin (1972).

General Model

Initially considering all variables discussed earlier and recalling Lave and Seskin's (1973) findings that the relationship appears to be linear, the following general mortality function is proposed:

$$\begin{aligned}
M_{a,s,r,c,i} = & b_0 + b_1 Y_{r,i} + b_2 E_{r,i} + b_c D_{a,s,r,i} + b_4 I_{r,i} \\
& + b_5 PD_i = b_6 TP_i + b_7 D_i + b_8 SO_{2i} + b_9 SS_i + b_{10} TEMP_i \\
& + b_{11} DMAX_i + b_{12} DMIN_i + b_{13} DDAYS_i + b_{14} TPRE_i + b_{15} (\#P.1+)_i \\
& + b_{16} (ER90+)_i + b_{17} (\#T32-)_i + b_{18} RHUM_i
\end{aligned} \tag{4}$$

where:

$M_{a,s,r,c,i}$ = the mortality rate for cause c, age group a, sex s, race r in area i. All independent variables are those previously discussed.

Table 2 summarizes the variables included in this general model.⁵² Indicated in this table are the acronyms used to designate the variables and, where a priori sign estimates can be made, the expected relationship of each independent variable to the dependent variable. A detailed description of each variable's derivation and their respective units of measurements is contained in the following section.

TABLE 2. SUMMARY OF INDEPENDENT VARIABLES INCLUDED IN GENERAL MODEL

Variable Name	Variable Description	A Priori Relationship to Dependent Variable: Direct (+) Inverse (-) or Uncertain (?)
Y	Per capita income	-
E	Percent of adult population with high school education	-
C	Per capita tobacco consumption	+
I	Percent of population with health insurance	-
PD	Population density	+
TP	Average annual concentration of total particulates	+
D	Average annual concentrations of dustfall	+
SO ₂	Average annual concentrations of sulfur dioxide	+
SS	Average annual concentration of suspended sulfates	+
TEMP	Average annual temperature	?
DMAX	Average daily maximum temperature	?
DMIN	Average daily minimum temperature	?
DDAYS	Average annual number of degree days	?
TPRE	Average annual precipitation	?
#P.01+	Average annual number of days with .01 inches or more precipitation	?
#T90+	Average annual number of days with maximum temperature 90° or greater	?
#T32-	Average annual number of days with maximum temperature 32° or less	?
RHUM	Average annual relative humidity	?

SECTION IV

ESTIMATING THE MODEL: RESULTS FOR ALLEGHENY COUNTY, PENNSYLVANIA

The preceding section demonstrated that the epidemiological approach was likely to be fruitful in the attempt to isolate ambient air quality's aggravation effect on human mortality. In addition, it was also suggested that regression analysis provided a useful technique to statistically control the numerous factors influencing mortality.

The objective of this section is the estimation of the general model. Using cross-sectional data from Allegheny County, Pennsylvania, these various mortality functions are estimated. Specifically, weighted linear regression analysis is used to estimate age-sex-race-cause-specific mortality functions. The results of this application are then discussed in terms of the physical social benefits (decreases in probability of death) to be expected from improvements in ambient air quality.

VARIABLE ESTIMATION, UNITS OF OBSERVATION AND DATA SOURCES

The procedures used to estimate the variables initially considered in the model and their data sources are presented below. All variables were obtained either directly at the census tract level or were estimated for the individual census tracts.

Census tracts were used as the primary unit of measurement because such divisions provide a more accurate assessment of the individual socio-economic factors believed to influence mortality.⁵³ The use of census tract data, however, limits the ability to control for individual's migration patterns. Thus, this approach implicitly assumes that if individuals moved during the period under study (1968-1972), the migration patterns were between areas of relatively equivalent air quality.⁵⁴

MR_{a,s,r,c,i}

All age-sex-race-cause-specific mortality rates were based on deaths occurring in Allegheny County, Pennsylvania during the five-year period 1968-1972. Separate mortality rates were estimated for overall, population-related and non-pollution-related causes of death. The causes of death considered pollution-related are presented in Table 3.

The required information was obtained from individual death certificates supplied by the Allegheny County Department of Public Health. These mortality rates were calculated using the following standard demographic procedures:⁵⁵

1. a. List total deaths for all individuals of age group a, sex s, race r who resided in census tract i at the time of their death during the period 1968-1972 (deaths);⁵⁶
 - b. List deaths from cause c in census tract i for this age, sex, race group during these years (cause); and
 - c. Multiply five times the 1970 population of age a; sex s, race r in census tract i (population). The reason for this step is that the procedure involves a five year average mortality rate and 1970 is the mid-year of this period. It is assumed that the changes in the population during this period occurred at a constant linear rate.
2. Add one-half of item 1.a (deaths) to the figure in item 1.c (population). This calculation provides an estimate of the population at risk at the beginning of the period and is based on the assumption that half the deaths precede the mid-point.
3. Divide the figure in item 1.b (cause) by the results of step 2 in order to obtain the desired mortality rate. Algebraically, this calculation may be written as:

$$MR = \frac{\text{Cause [1.b]}}{\text{Population [1.c]} + \frac{\text{Deaths [1.a]}}{2}} \quad (5)$$

TABLE 3. UNDERLYING CAUSES OF DEATH CONSIDERED TO BE RELATED TO AIR POLLUTION

Underlying Cause of Death	I.C.D.A. Codes*
Tuberculosis of the respiratory system	010-012
Malignant neoplasms of buccal cavity and pharynx	140-159
Malignant neoplasms of respiratory system	160-163
Major cardiovascular diseases	390-448
Acute bronchitis and bronchiolitis	446
Chronic and unqualified bronchitis	490-491
Emphysema	492
Asthma	493

* Based on Eighth Revision of the International Classification of Diseases, Adapted 1965.

It should be recognized that the rationale for using a five year average mortality rate is that it will help reduce the variance in these rates caused by small and differing sample sizes (population of the census tracts). This is an important consideration since the stability of these mortality rates rather than their absolute size is essential. Illustrative of this concern is a census tract with twenty individuals one of whom dies during our five-year study. In this case the five year average mortality rate will be 1/100 although the yearly rates will be highly unstable ranging from 1/20 to zero (undefined).

These age-sex-race-cause-specific mortality rates were calculated for three age groups (less than 45, 45-64 and 65 and older) although only for white males and females. The reason for excluding non-whites was the small sample size in the population of Allegheny County.⁵⁷

Y_{ri}

The 1969 per capita income for race r in census tract i was calculated from data contained on the 1970 Census of Population and Housing Summary Tapes - First Count (Census Tapes).

$E_{r,i}$

The percentage of the population of race r , 25 years old and over, in census tract i with at least high school education was calculated from data contained on the Census Tapes.

$C_{a,s,r,i}$

The estimated tobacco consumption per capita for age group a , race r in census tract i was estimated from data in the 1963-1972 Panel Studies of Income Dynamics. The estimates used were the national average expenditure on tobacco by individuals of age a , sex s , race r , with an income equivalent (to the nearest \$1,000) to Y_{ri} .⁵⁸ This estimation procedure assumes that Allegheny County is typical of the nation as a whole.

$I_{r,i}$

The estimated percentage of the population of race r in census tract i with some type of health insurance. This variable was estimated using the 1969 family income of the individual families of race r in census tract i and the data in Table 4 which is based on national averages. It was assumed that the same percentage holds for all individuals of race r in census tract i . These estimates were then summed for all Allegheny County census tracts and the total number of individuals with some form of hospitalization estimated using this procedure was verified with a control total supplied by Blue Cross of Western Pennsylvania.⁵⁹ This comparison revealed only a slight differential (6 percent).

TABLE 4. PERCENTAGE OF HOUSEHOLDS WITH SOME FORM OF
HEALTH INSURANCE BY HOUSEHOLD INCOME*

Household Income	Percent of Households With Some Health Insurance
L.E. \$ 1,500	37.3
G.T. \$ 1,500 - L.E. \$ 2,500	48.8
G.T. \$ 2,500 - L.E. \$ 3,500	62.5
G.T. \$ 3,500 - L.E. \$ 4,500	73.1
G.T. \$ 4,500 - L.E. \$ 5,500	79.8
G.T. \$ 5,500 - L.E. \$ 6,500	83.0
G.T. \$ 6,500 - L.E. \$ 7,500	84.5
G.T. \$ 7,500 - L.E. \$ 8,500	85.5
G.T. \$ 8,500 - L.E. \$ 9,500	87.3
G.T. \$ 9,500 - L.E. \$10,500	88.9
G.T. \$10,500 - L.E. \$11,500	87.8
G.T. \$11,500 -	88.2

* This table was derived from data presented by Rosett and Huang (1973).

PD₁

Three alternative measures of population density (crowding) were utilized. The first of these variables was population per square mile in census tract i (P/mi_1^2).⁶⁰ This figure was calculated by dividing the total 1970 population of census tract i by the area of tract i in square miles.⁶¹ The second proxy for a crowding variable, population per room ($P/R_{1,r}$) in census tract i of race r, was calculated by dividing the population of race r in census tract i by the total number of rooms occupied by the individuals of race r in census tract i. The third crowding variable proxy, population per residential area (P/RA_1) in census tract i, was calculated by dividing the 1970 census population of census tract i by the total residential area (square miles) in census tract i.

TP

The five year arithmetic mean of annual averages of total particulates in ug/m^3 , for the calendar years 1968-1972 was calculated for each census tract using the procedure described below.

1. Calculate the five-year average of annual arithmetic means by monitoring station. (Use the average values for a



Figure 1. Location of air quality monitoring stations within Allegheny County, 1968-1972.

specific individual station to estimate missing values for the station.)

2. Locate the individual monitoring stations on a map according to USGS coordinates. (See Figure 1)
3. Estimate values for the remaining points in Allegheny County using the SYMAP computerized mapping program. The interpolation procedure used by this program involves calculating the weighted averages of slopes from values of nearby data points developed by a gravity-type model and modified to consider distance and direction.⁶²
4. Plot these interpolated values on a map of Allegheny County in order to facilitate the estimation of average values for each census tract.
5. Calculate the average value of the total particulates by super-imposing a clear overlay on the computer-generated map. Sum the values of individual point estimates and divide by the number of points.

The original data on total particulates was collected at the individual air monitoring stations operated by the Allegheny County Bureau of Air Pollution Control. The number of monitoring stations employed ranged from four in 1968 to fourteen in 1972. Measurements were in micrograms per cubic meter and based on hi-volume sampler readings. In order to determine if the original data points were sufficiently dispersed for meaningful cartographic data portrayal, SYMAP provided an estimate of a "point distribution coefficient". Essentially, a point distribution coefficient of 0.0 indicates a complete cluster (all observations located at one point) while a value of 2.2 indicates a square lattice (distributed regularly in a hexagonal pattern). The value of this coefficient for the data points used to extrapolate the census tract estimates of the various air quality variables was 0.75. This estimate indicates that while the data points used for extrapolation were slightly clustered, their spatial distribution was approaching a random distribution. Thus, although not ideally dispersed, the monitoring stations are sufficiently dispersed to assure relatively accurate extrapolations.⁶³

It should be noted that the use of air quality measurements coincident with the potential mortality effects under study implicitly assumes that either average air quality has been relatively constant over the preceding years or that the preponderance of air quality's influence on mortality is experienced almost immediately. The latter possibility has received support from the investigation conducted by Brown, et al. (1975) concerning the mortality effects resulting from the 1974 fuel crisis. Specifically, the authors tested whether decreases in vehicular exhaust fumes would have beneficial short-term health effects. Their analysis uncovered decreases in first quarter 1975 mortality rates for Alameda County, California, ranging from 11.2 percent for cardiovascular diseases to 38 percent for chronic lung disease.

D_i

The five year arithmetic mean of annual averages of dustfall (soluble and insoluble) in tons/square mile/month for the calendar years 1968-1972 was calculated for each census tract using the procedures outlined above for total particulates. Data was collected at the individual air monitoring stations operated by the Allegheny County Bureau of Air Pollution Control. The number of monitoring stations ranged from forty-nine in 1968 to five in 1972. Measurements were in tons per square mile and calculated by weighing monthly samples of particulate matter collected in dustfall jars.

SO_{2i}

The five year (1968-1972) arithmetic mean of annual averages of sulfur dioxide in PPT/24 hours for the calendar years 1968-1972 was calculated for each census tract using the same procedures applied to total particulates. Data was collected at the individual air monitoring stations operated by the Allegheny County Bureau of Air Pollution Control. The number of monitoring stations ranged from forty-two in 1968 to forty-seven in 1972. Measurements were based on the sulfation rates of lead peroxide candles and converted to PPT SO₂/24 hours by application of the Foran and Gibbon conversion factors for the years 1968-1971 and from Huey Plates in 1972.

SS_i

No estimate of suspended sulfates was available; therefore, this variable could not be included.

Climatological Variables

The five year (1968-1972) arithmetic mean of all climatological variables were calculated for each census tract using the same procedure applied to total particulates. The original data was collected at five monitoring stations (three in Allegheny County and two in neighboring counties) operated by the U.S. Department of Commerce. The following list represents the climatological variables used in this study:

- TEMP - average annual temperature
- DMAX - average daily maximum temperature
- DMIN - average daily minimum temperature
- DDAYS - average annual number of degree days
- TPRE - average annual precipitation
- #P.1+ - average annual number of days with 0.1 inches or more precipitation
- #T90+ - average annual number of days with maximum temperature 90° or greater

#T32 - average annual number of days with minimum temperature
32° or less

RHUM - average annual relative humidity.

ESTIMATION

The general model developed in Section III was estimated using the variables described in the preceding section. Specifically, eighteen age-sex-race-cause-specific linear mortality functions were estimated using weighted regression analysis.⁶⁴ The rationale for using weighted regression analysis was to correct the problems of non-constant variance of the error term (heteroscedasticity). The existence of heteroscedasticity violates the assumptions of ordinary least-squares regression analysis thereby introducing biases into the estimated results.⁶⁵ Smith has demonstrated how this problem enters into cross-sectional analysis as well as the appropriate procedure for eliminating heteroscedasticity.⁶⁶

Since the death rate is a proportion (or a proportion times a constant), the variance of the observed death rate would be σ^2/N where σ^2 is the variance of a proportion and N is the sample size. Assuming that σ^2 is appropriately the same for all samples for a given age group, then the variance of the observed death rate is inversely proportional to the sample size. In the regression, instead of minimizing the sum of squares of errors, $\sum E_i^2$ where E_i is the difference between observed death rate and estimated death rate, one wishes to minimize $\sum E_i^2$ (σ^2/N_i), which, assuming σ is constant, will be minimized when $\sum E_i^2 N_i$ is minimized or when $\sum (E_i N_i^{1/2})^2$ is minimized. This means the errors should be weighted by a factor equal to the square root of the sample size.⁶⁷

Following Smith's example, each of the observations were weighted by the square root of the sample size since this linear weighted regression analysis resulted in the "best" estimate.⁶⁸ For example, all the independent variables associated with white male mortality in the over sixty-five age group in each observation were multiplied by the square root of the white male population over sixty-five in the corresponding census tract.

In the regressions which follow, several candidate variables were excluded from the equations. Three alternative crowding variables (P/Mi², P/R, P/RA) and two measures of the dirtiness of air pollution (D,TP) were initially considered. Final selection of variables P/RA and TP was based on statistical significance requirements. Similar reasoning was also applied to the selection of the climatic variables #P.1+, and #T32- from among the nine originally considered (TEMP, DMAX, DMIN, DDAYS, TP, #P.1+, #T90+, #T32-, and RHUM), since there was no a priori preference. In the cases of Y and I, the decision not to include these variables was based on the desire to avoid the effects of multicollinearity.⁶⁹ Specifically, both

of these variables were highly correlated with E (e.g., the simple correlation coefficient between E and Y was .8 while that between E and I was .4). Since no observations were available on SS, this variable could not be estimated. The estimates for C were extremely unreliable; and, therefore, when it was determined to be statistically insignificant, the variable was deleted. To facilitate the discussion which follows, the means and standard deviation of the variables included in the various mortality functions are presented in Table 5.

TABLE 5. MEANS AND STANDARD DEVIATIONS OF VARIABLES INCLUDED IN EQUATIONS

Variable	Mean	Standard Deviation
Percent of adult white population with high school education	52.063	16.122
Total ₃ particulates (ug.m ³)	122.571	15.381
Sulfur dioxide (PPT/24 hrs.)	37.860	8.933
Number of days precipitation > 0.1"	83.117	2.542
Number of days maximum temperature < 32°	34.709	2.759
Population per .01 sq. mi. (residential)	212.895	189.530

RESULTS

The results of the weighted linear regression analysis using the final set of independent variables (E, SO₂, TP, #P.01+, #T32-, and P/RA) regressed on the various age-sex-cause-specific white mortality rates are presented in Table 6. The figures in parenthesis represent the student t-values associated with each coefficient and $\bar{R}^2$ is the (corrected) coefficient of determination. The statistical significance of each variable's coefficient is indicated by the use of asterisks. The inclusion of additional candidate independent variables for each mortality function did not significantly increase the equation's overall explanatory power ($\bar{R}^2$). The percent of the variance in the dependent variables explained by the individual regressions presented in Table 6 range from 1.2 percent for white female non-pollution-related causes of death in the less than forty-five age group to over 51 percent for white male overall mortality in the sixty-five and over age group. The reason for the separation of overall mortality rates into pollution and non-pollution-related causes is, as stated earlier, that a priori air quality can only be

TABLE 4. MORTALITY FUNCTION ESTIMATES*
(1968-1972 ALLEGHENY COUNTY, PENNSYLVANIA)

Variable	Less than 45		45-64		65 and Over	
	Male	Female	Male	Female	Male	Female
PART A. WHITE OVERALL MORTALITY FUNCTIONS						
Percent of adult population with high school education	-3.907 (6.994)*	-1.693 (3.828)*	-17.003 (8.166)*	-6.850 (6.472)*	-45.141 (6.395)*	-17.348 (3.217)*
SO ₂ (PPT/24 hrs.)	-1.206 (1.294)**	0.056 (0.083)	1.747 (0.474)	0.408 (0.245)	-0.466 (0.041)	-1.056 (0.116)
Total particulates (ug/m ³)	0.766 (1.500)**	0.267 (0.726)	5.632 (2.712)*	3.373 (3.469)*	14.244 (2.036)*	13.276 (2.281)*
Number of days precipitation $\geq .1"$	0.649 (0.218)	2.076 (0.968)	25.344 (2.099)*	10.218 (1.814)*	107.875 (2.661)*	34.347 (1.017)
Number of days maximum temperature $\geq 32^\circ$	-1.521 (0.678)	-0.405 (0.245)	-3.174 (0.318)	-2.334 (0.493)	-62.560 (1.874)*	-42.924 (1.565)**
Population per sq. mi. (residential)	0.218 (1.490)	0.158 (3.300)*	1.056 (4.426)*	0.334 (3.173)*	0.711 (1.134)	-0.158 (0.319)
Constant	371.653 (1.360)**	13.340 (0.067)	-332.125 (0.296)	-246.402 (0.470)	1247.897 (0.335)	3168.511 (1.003)
R ²	.173	.024	.338	.370	.514	.453
PART B. WHITE POLLUTION-RELATED CAUSE-SPECIFIC MORTALITY FUNCTIONS*						
Percent of adult white population with high school education	-1.348 (4.604)*	-0.569 (2.706)*	-11.565 (7.397)*	-5.021 (7.558)*	-31.158 (6.223)*	-13.181 (3.209)*
SO ₂ (PPM/24 hrs.)	0.043 (0.087)	0.031 (0.097)	1.832 (0.617)	0.265 (0.253)	1.014 (0.116)	2.683 (0.386)
Total particulates (ug/m ³)	0.500 (1.067)*	0.244 (1.995)*	4.014 (2.693)*	1.570 (2.577)*	10.291 (1.097)*	4.514 (2.146)*
Number of days precipitation $\geq .1"$	-0.806 (0.325)	1.276 (1.202)*	20.723 (2.392)*	3.970 (1.123)	64.891 (2.063)*	26.136 (1.00)
Number of days maximum temperature $\geq 32^\circ$	1.104 (0.438)	-0.286 (0.364)	-3.873 (0.542)	1.595 (0.536)	-41.626 (1.619)**	-30.642 (1.467)**
Population per sq. mi. (residential)	0.037 (1.116)	0.050 (2.144)*	0.609 (1.556)*	0.208 (3.167)*	0.332 (0.602)	-0.162 (0.429)
Constant	105.106 (0.734)	-117.480 (1.178)	-540.919 (0.477)	42.982 (0.130)	1796.121 (0.590)	2124.704 (0.883)
R ²	.161	.017	.278	.330	.483	.425
PART C. WHITE NON-POLLUTION RELATED CAUSE-SPECIFIC MORTALITY FUNCTIONS**						
Percent of adult white population with high school education	-2.560 (5.493)*	-1.124 (3.102)*	-6.738 (6.754)*	-1.829 (3.092)*	-13.982 (6.076)*	-4.167 (2.188)*
SO ₂ (PPT/24 hrs.)	-1.249 (1.752)*	0.025 (0.045)	0.115 (0.074)	0.141 (0.154)	-1.480 (0.368)	-3.739 (1.162)
Total particulates (ug/m ³)	0.267 (0.683)	-0.082 (0.272)	1.619 (1.849)*	1.403 (3.377)*	3.953 (1.585)**	3.762 (1.830)*
Number of days precipitation $\geq .1"$	1.156 (0.508)	0.340 (0.194)	4.622 (0.904)	6.248 (1.984)*	42.985 (2.974)*	8.811 (0.726)
Number of days maximum temperature $\geq 32^\circ$	-2.625 (1.530)**	-0.119 (0.088)	0.700 (0.166)	0.740 (0.279)	-29.734 (1.747)*	-12.282 (1.268)
Population per sq. mi. (residential)	0.182 (3.800)*	0.108 (2.755)*	0.447 (4.424)*	0.125 (2.125)*	0.379 (1.696)*	0.004 (0.022)
Constant	266.346 (1.276)	124.797 (0.766)	208.791 (0.442)*	-299.364 (0.987)	-480.228 (0.346)	1043.817 (0.935)
R ²	.100	.021	.280	.307	.377	.340

* All mortality rates (dependent variables) are in deaths per 100,000.

** Significant at 0.05 probability level (two-tailed test).

*** Significant at 0.10 probability level (two-tailed test).

† These mortality rates are based on total deaths from tuberculosis of the respiratory system, malignant neoplasms of buccal cavity, pharynx and respiratory system, major cardiovascular disease, acute and chronic bronchitis and bronchiolitis, emphysema and asthma.

†† These mortality rates are based on total deaths from all causes other than tuberculosis of the respiratory system, malignant neoplasms of the buccal cavity, pharynx and respiratory system, major cardiovascular disease, acute and chronic bronchitis and bronchiolitis, emphysema and asthma.

expected to influence the probability of death from certain causes (e.g., respiratory diseases) while supposedly having no discernable effect on others (e.g., motor vehicle accidents).

Part A of Table 6 presents the results of applying the general model to overall white mortality and is analogous to the Lave and Seskin results presented earlier.⁷⁰ The signs of the coefficient for all variables are as expected with the exception of SO_2 for males less than forty-five, SO_2 for males and females sixty-five and over, and P/RA for females sixty-five and over. In general the absolute value of most coefficients increases with age as does the R^2 . The increase in R^2 is probably the result of both the inverse relationship between accidental deaths and age and the direct relationship between sample size (number of deaths) and age. The unexpected negative sign of SO_2 for males less than forty-five could be due to the fact that younger people dies primarily from non-pollution-related causes.

In order to test this hypothesis, separate mortality functions were estimated for pollution related (Table 6, Part B) and non-pollution-related (Table 6, Part C) causes of death using the same model as for overall mortality.⁷¹ This procedure allows the testing of this hypothesis since the coefficients of the variables in the overall mortality function are simply the sum of the coefficients from the pollution-related and non-pollution-related mortality functions.

For the pollution-related causes of death all air pollution variables have the expected sign, thus indicating that air quality exacerbates these types of illnesses regardless of age. It is also noteworthy that generally the coefficients increase with age indicating that possibly the absolute effect of air pollution is greater on the elderly or that there exists a cumulative effect of exposure to air pollution. Part C of Table 6 confirms the assertion that the coefficients obtained for overall mortality variables are simply the sum of pollution-related and non-pollution-related causes of death. The signs of the air pollution variables' coefficients in Part C are of little other concern since these causes were not expected to be affected by air quality.

To achieve a clearer interpretation of the results attained from applying the general air pollution-mortality model to Allegheny County and thereby addressing many of the salient issues regarding the air pollution-mortality question, each independent variable must be examined. Specifically, the remainder of this section analyzes the estimated coefficients for the various independent variables in order to derive a better understanding of the theoretical and policy implications associated with responses in human mortality resulting from differences in air quality.

E

The percentage of the adult white population with a high school education is inversely related to all mortality rates. Using the pollution-related mortality function for white males sixty-five and over as an example, an increase of 1 percent of the adult white population with a high school

education will lead to a decrease of approximately thirty-one pollution-related deaths per annum for every 100,000 males in this age-race group.

The coefficients of E are highly significant (as indicated by the t statistics in parenthesis below the coefficient) in all mortality functions.⁷² It may thus be concluded that the effect of education is significantly different from zero and inversely related to mortality; thereby suggesting that more education results in increased quantity and/or quality of medical care at the preventive stages of an illness. The high correlation of education with income also suggests the possibility that higher quality goods which favorably affect mortality are consumed by the higher educated groups. In essence, these results confirm those obtained by Kitagawa and Houser (1968), Fuchs (1965, 1973) and Auster, *et al.* (1969).

It should be recognized that while the absolute magnitude of the coefficient of E for the overall mortality functions are the largest of the three mortality functions, such a result is to be expected. It is also interesting to note that the absolute size of E's coefficient is larger (indicating a lower probability of death, *ceteris paribus*) for pollution-related causes than for non-pollution-related causes regardless of sex after age forty-five. This result may be attributable to favorable occupational and/or residential exposure to air pollution on the part of more educated individuals. The probability of occupational differentials is reinforced by analysis of the sex differentials in the absolute size of E. Specifically, the male coefficients are absolutely larger than the female coefficients indicating that males with more education may enjoy significantly less hazardous occupations.

SO₂

The coefficients of sulfur dioxide (SO₂) are not significant for any of the pollution-related mortality functions. Thus, it may not be concluded that the effect of SO₂ is significantly different from zero or that SO₂ is positively related to mortality. This result does not imply that SO₂ has no impact on mortality. In fact, this result may indicate that SO₂ requires a carrier (e.g., particulate matter) in order to enter the body and exhibit its deleterious effects or that concentrations found in Allegheny County during the 1968-1972 period were not intense enough to induce a statistically significant effect. It should be noted that when a multiplicative interaction term between SO₂ and TP was used in the regression analysis, the coefficient of this synergistic variable was predominately positive and significant at the 0.15 probability level (two-tailed test). The overall equation using this multiplicative variable, however, was not as statistically reliable as when separate air quality terms were used.⁷³

Even though the estimated SO₂ coefficients are statistically insignificant, they warrant further discussion since SO₂ has been widely considered a major contributor to air pollution's adverse health effects. SO₂ exhibits the expected positive relationship to pollution-related mortality although SO₂ is often inversely related to non-pollution-related mortality (three of the six coefficients have negative signs). No *a priori* rationalization for a

positive relationship between SO₂ and non-pollution-related causes of death exists. Consequently, the predominance of negative signs is not unexpected. The negative coefficient obtained for males less than forty-five and both males and females sixty-five and over in the over-all mortality functions, however, is to be expected since this coefficient is the sum of the coefficients from both the pollution-related and non-pollution-related mortality functions. Indeed, it is because of this intrinsic summation process and the fact that most deaths in the less than forty-five age group are from non-pollution-related causes (see Table 7) that similar negative coefficients were obtained by Lave and Seskin (1970b) for minimum sulfates in the fifteen to forty-four age group.⁷⁴ Using the pollution-related mortality function for white males sixty-five and over as an example, an increase of average annual SO₂ concentrations by one PPT/24 hours will result in an increase of approximately one pollution-related death per annum for every 100,000 males in this age group.

TABLE 7. AGE-SEX-CAUSE DISTRIBUTION OF ALLEGHENY COUNTY
WHITE DEATHS DURING 1968-1972*

Deaths	Less than 45		45-64		65 and Over	
	Male	Female	Male	Female	Male	Female
Overall	3,555 (100)	2,203 (100)	13,647 (100)	7,636 (100)	25,604 (100)	25,596 (100)
Pollution-related	757 (21)	440 (20)	8,976 (66)	3,752 (50)	18,261 (71)	18,463 (72)
Non-pollution related	2,798 (79)	1,763 (80)	4,671 (34)	3,884 (50)	7,343 (29)	7,133 (28)

*Figures in parentheses are percentage of column total.

It should also be recognized that the size of the SO₂ coefficients generally increase with age for all pollution-related mortality functions, and that these SO₂ coefficients are constantly larger for pollution-related mortality functions than for the non-pollution-related mortality functions. As Table 7 indicates, the increase in the size of the coefficients with age is to be expected since the number of individuals dying from pollution-related causes increases with age. The probable explanations for these results are that: (1) the ability of the body to withstand the influence of SO₂ decreases with age, or (2) there exists a cumulative influence of SO₂ on mortality.⁷⁵

TP

Total particulate predominately exhibits the expected positive relationship to all mortality rates although TP is inversely related to non-pollution-related mortality for females in the less than forty-five age group. Since no a priori rationalization for a positive relationship between TP and non-pollution-related causes of death exists, the presence of the negative sign for females less than forty-five is not unexpected. Using the pollution-related mortality function for elderly white males as an example, an increase of average annual TP concentrations by one μm^3 will result in an increase of approximately ten pollution-related deaths per annum for every 100,000 males in the sixty-five and over age group.

It should also be recognized that the size of the TP coefficients is generally larger for the pollution-related mortality functions than for the non-pollution-related mortality functions. The coefficients of TP increase with age for all mortality functions and not just pollution-related as is the case with SO_2 's coefficients. As Table 7 indicated, this result is to be expected since the number of individuals dying from all causes, especially pollution-related, increases with age. The probable explanation of this result is that: (1) the ability of the body to withstand the influences of TP decreases with age, or (2) there exists a cumulative influence of TP on mortality.

The observed sex-differential in the size of the TP coefficient suggests the possibility of relatively higher exposure levels at work for males compared to exposure levels experienced by females in the residential environment.⁷⁶ In essence, this result suggests that if potential sexual differences in response to air pollution are ignored, the "true" effect of TP on mortality (estimated at the place of residence) is that level represented by the female coefficient. Since it is impossible, however, to discount the potential sexual differences in response, the estimated male and female coefficients should be considered valid.

The coefficients of TP are generally statistically significant for most of the mortality functions. The exceptions occur in the less than forty-five age group where the female overall and non-pollution-related coefficients and the male non-pollution-related coefficients are not significantly different from zero at the 0.20 probability level (two-tailed test). The relative insignificance of this variable for this group can be attributed to the comparatively small sample on which the mortality rates are based. Therefore, it can be concluded that (in general) the effect of TP is significantly different from zero and positively related to mortality, especially pollution-related mortality.

#P.1+

The number of days with precipitation greater than 0.1 inch is directly related to all mortality rates except that of the male less than forty-five age group for non-pollution-related mortality. Again using the pollution-related mortality function for elderly white males as an example, an annual increase of one day with precipitation greater than 0.1 inch will result in an increase of almost sixty-five pollution-related deaths among white males sixty-five and older per annum for every 100,000 males in this age group.

The coefficients of #P.1+ are significant in eight of the sixteen mortality functions. In these cases, the coefficients of #P.1+ are significant at the 0.50 probability level. Therefore, it cannot be generally concluded that the effect of rainfall is significantly different from zero and directly related to mortality.

It should also be noted that the absolute size of the coefficients increase with age and are consistently larger for males in each age-cause mortality function. These results indicate that the elderly and males are more severely impacted by rainfall. The probable explanations of these results are that: (1) the ability of the body to withstand the influence of damp weather decreases with age; and (2) males, due to their working environment, tend to be exposed more often to damp weather.

#T32-

The number of days that maximum temperature is 32° or less is negatively related to mortality in thirteen of the eighteen mortality functions estimated and positively related in the remainder of the mortality functions. It appears that these results, together with the fact that #32- is only significantly different from zero in less than 50 percent of the cases examined, can only be explained by asserting that cold weather influences various age-sex groups differently. Again using the sixty-five and older, pollution-related white male mortality estimates as an example, an increase of one day per year with a maximum temperature equal to or less than 32° will result in a decrease of forty-two pollution-related deaths per annum for every 100,000 males in this age group, a result that would not generally have been expected.

P/RA

Population per 0.01 square miles of residential land area predominantly exhibits a positive relationship to mortality although P/RA is inversely related to female over sixty-five mortality from pollution-related and overall causes. Since the *a priori* expectation was for a positive relationship between population density and mortality, these negative coefficients were unexpected. However, none of the negative coefficients are significantly different from zero at the 0.20 probability level. All P/RA coefficients in the forty-five to sixty-four age group are positive and significantly different from zero at the 0.05 probability level. Thus, it can be concluded that population density generally increases the probability of death for the more mobile age groups (less than sixty-five), probably caused by increasing exposure to a variety of diseases.

Elasticities

Another interesting way of viewing the regression results presented in Table 6 is in terms of the elasticities of the independent variables. Specifically, elasticity estimates facilitate the comparison of effects from a single explanatory variable on a variety of dependent variables (mortality rates). Table 8 presents the elasticities (calculated at the mean) of each explanatory variable in the various age-sex-cause-specific white mortality functions. Using the standard example, the earlier results may be

reinterpreted as estimating that a 10 percent increase in each of the independent variables will produce the following percentage changes in annual elderly white male population-related mortality rates:

E(-3.0), SO₂ (+0.1), TP (+2.3), #P.1(+10.0), #32-(-2.7), and P/RA(+0.1).

It can also be seen from Table 8 that the effects of TP on the various pollution-related mortality rates is generally greater than TP's effect on non-pollution-related mortality rates. From the estimates in Table 8, it can also be concluded that TP have a larger relative effect on all pollution-related mortality rates than SO₂ even if the estimated SO₂ coefficients were statistically significant. Possible explanations for this result is that some of the particulate matter located in Allegheny County may be independently and inherently harmful (e.g., asbestos) or that the particulate matter acts as a carrier of other hazardous elements.

Finally, the weight of the evidence from Allegheny County suggests that long-term low-level dosages of air pollution, measured as TP and SO₂, do in fact have exacerbating effects on certain (pollution-related) causes of death. These effects, while small in absolute terms, are statistically significant for TP although statistically insignificant for SO₂ when SO₂ is considered as a separate independent variable.

Therefore, based on the results obtained for Allegheny County, it may be expected that an improvement in ambient air quality will produce social benefits in the form of decreased probabilities of death. These potential mortality reductions, in addition to the numerous other potential costs and benefits, must be further evaluated in order to determine the socially optimum level of air quality. While detailed analysis of these other costs and benefits is beyond the scope of this study, the current effort will concentrate on the development and application of criteria to facilitate the efficient use of society's scarce air resource.

TABLE 8. ELASTICITY ESTIMATES

	Less than 45		45-64		65 and Over	
	Male	Female	Male	Female	Male	Female
Part A. Independent Variables from White Overall Mortality Functions						
Percent of Adult White Population with High School Education	-0.77	-0.58	-0.54	-0.43	-0.31	-0.17
Sulfur Dioxide	-0.02	0.01	0.04	0.02	-0.002	-0.01
Total Particulates	0.36	0.22	0.40	0.50	0.23	0.31
Number of Days Precipitation > .1 inch	0.20	1.13	1.23	1.03	1.18	0.55
Number of Days Maximum Temp. < 32°	-0.20	-0.09	-0.06	0.10	-0.29	-0.28
Population per .01 sq. mi. (Residential)	0.18	0.22	0.13	0.09	0.02	-0.01
Part B. Independent Variables from White Pollution-Related Cause-Specific Mortality Functions						
Percent of Adult White Population with High School Education	-0.69	-0.62	-0.53	-0.63	-0.30	-0.19
Sulfur Dioxide	0.02	0.02	0.05	0.02	0.01	0.03
Total Particulates	0.59	0.89	0.44	0.46	0.23	0.31
Number of Days Precipitation > .1 inch	-0.41	3.01	1.53	0.80	1.00	0.57
Number of Days Maximum Temp. < 32°	0.38	-0.21	-0.12	0.13	-0.27	-0.28
Population per .01 sq. mi. (Residential)	0.08	0.22	0.11	0.11	0.01	-0.01
Part C. Independent Variables from White Non-Pollution-Related Cause-Specific Mortality Functions						
Percent of Adult White Population with High School Education	-0.82	-0.56	-0.60	-0.23	-0.32	-0.15
Sulfur Dioxide	-0.29	0.01	0.01	0.01	-0.02	-0.10
Total Particulates	0.20	-0.10	0.35	0.53	0.21	0.32
Number of Days Precipitation > .1 inch	0.50	0.27	0.67	1.26	1.56	0.50
Number of Days Maximum Temp. < 32°	-0.56	-0.04	0.04	0.06	-0.31	-0.29
Population per .01 sq. mi. (Residential)	0.24	0.22	0.17	0.06	0.04	0.00

SECTION V

COST-BENEFIT ANALYSIS: ECONOMIC GUIDELINES FOR SOCIAL DECISIONS

Preceding sections have provided insights on both the economic nature of the air pollution problem and air pollution's impact on human mortality. It was also demonstrated that some form of collective action was needed in order to achieve efficient resource allocation and thus facilitate an increase in social welfare. Specifically, the second section concluded that because of the inherent "public good" characteristic of the scarce resource clean air, no private market allocative mechanism has developed, primarily due to the high costs involved in negotiating property rights when the exclusion principle is not applicable. A response to this situation may take the form of either a collection of tax-subsidy schemes or direct regulatory policies.⁷⁷ Therefore, the primary concern of this section is to identify specific criteria that should be used to guide the suggested governmental intervention. This section analyzes the theoretical foundations of cost-benefit analysis in order to provide a basis for later monetization of the estimated changes in human mortality resulting from changes in ambient air quality.

COST-BENEFIT ANALYSIS--THE THEORY

Economics provides certain analytical techniques that can be employed to assist governmental decision makers concerned with the problem of allocating scarce resources such as clean air. Collectively, these techniques are known as cost-benefit analysis. The objective of these procedures is to maximize social welfare or "to maximize the present value of all benefits less that of all costs, subject to specific constraints".⁷⁸ Specifically, the question is one of assessing whether social welfare would be enhanced with the anticipated governmental action rather than in the absence of such market intervention.⁷⁹ Since changes in welfare are contingent upon changes in utility, "the problem therefore becomes one of assessing the impact of policy changes on individuals' utility levels as well as that of determining the net change in welfare from a set of changes in utility levels".⁸⁰ The primary economic concept traditionally employed to assess perturbations in utility is consumer's surplus. Consumer's surplus, together with the various compensation principles developed by economists, form the theoretical bases for current cost-benefit analysis. Each of these principles will be discussed in the following sections in order to demonstrate that cost-benefit analysis is based on a consistent conceptual framework rather than simply being a set of arbitrary rules and procedures. It is only by definitively examining the theoretical cornerstones of cost-benefit analysis that the existing literature concerning the dollar costs of pollution-induced mortality can be evaluated and the frontiers of knowledge

expanded. The theoretically correct quantification of these costs is an essential prerequisite in guiding government allocation of the scarce resource clean air and as such is a major contribution of the current research.

Consumer's Surplus

The idea of expressing a gain (loss) in terms of money income that accrues to the consumer as a result of a fall (rise) in the price of a particular good originated with Dupuit in 1844.⁸¹ It was Marshall, however, who popularized and refined the concept commonly known as consumer's surplus. The essential elements of Marshall's presentation may best be illustrated using Figure 2. Employing classical utility theory and the assumptions of diminishing marginal utility and constant amounts of all other goods consumed, the curve MM' represents the marginal utility derived from the consumption of good X . If it is further assumed that the marginal utility of money is constant, the individual will maximize his utility at any price of X by purchasing all units for which the marginal utility exceeds price multiplied by the marginal utility of money. Given the constant marginal utility of money,⁸² the vertical axis can be expressed in terms of money thereby transforming MM' into the demand curve for X . If the individual were originally in equilibrium at point A and the price of X were decreased from P_1 to P_2 , the surplus that would be received from the last $(X_2 - X_1)$ units of X purchased would be equal to his total change in utility $(X_1 ABX_2)$ minus the cost incurred $(X_1 CBX_2)$ or ABC . In addition to this surplus, the individual also benefits by an amount equal to P_2P_1AC due to the decrease in price on the first X_1 units of X . This results in a total consumer's surplus of P_2P_1AB . Using similar analysis, it can be demonstrated that the consumer's surplus for the first X_1 units of X is equal to P_1MA , the area under the demand curve above the price line.

The unrealistically strict assumption associated with Marshall's methodology fostered much dissatisfaction. Specifically, since the analysis assumes constant marginal utility of money and ignores the effects of changes in real income resulting from price changes, the approach represented an undesirable method of assigning a dollar value to changes in utility and hence welfare. Alternative and more theoretically acceptable measurement techniques have since been developed, primarily by Hicks (1944 and 1956).

The methods developed by Hicks for expressing consumer's surplus can most easily be expressed with the aid of the individual's indifference map shown in Figure 3. In this figure, the numeraire (or money) is measured on the vertical axis and X , the commodity in question, on the horizontal axis. Assuming that the individual received an income of OM and that the price of X is originally P_1 or OM/OX_3 , equilibrium is achieved at point A on indifference curve I where the individual's MRS is equal to the MRT or the slope of his budget constraint (MX_3) . If the price of X decreases from P_1 to P_2 or OM/OX_4 , maintaining constant money income (OM), the individual will increase his consumption from X_1 to X_2 and attain an equilibrium position at point B on indifference curve II where his MRS is equal to his new budget constraint (MX_4) . This increase in utility (i.e., movement from

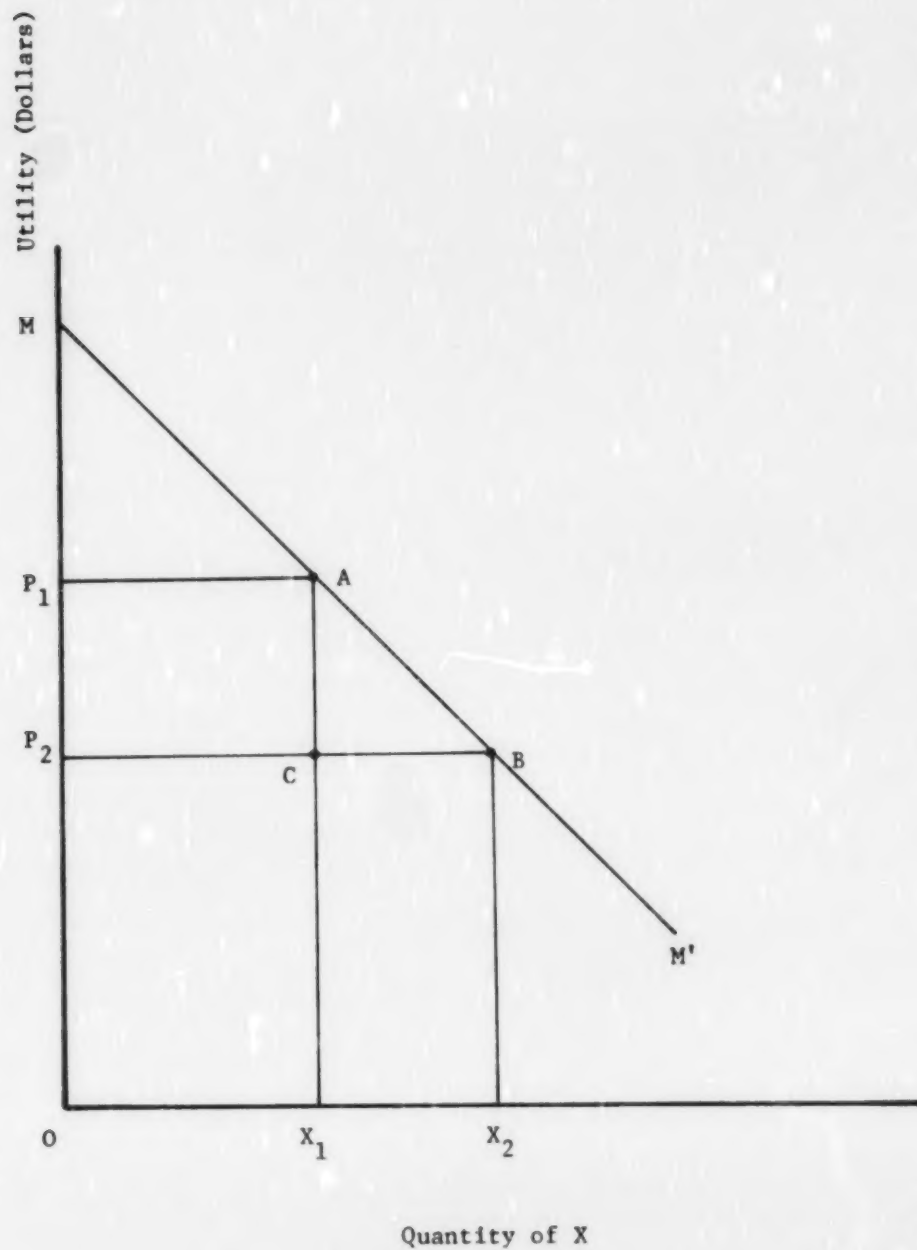


Figure 2. Marshallian consumer's surplus.

indifference curve I to indifference curve II) represents his change in consumer's surplus. The problem associated with this method of assessing consumer's surplus is in the conversion of the changes in utility to monetary units. In order to determine the dollar value of this increase in utility Hicks developed four different measures of consumer's surplus.

The first method is termed the price-compensating variation (PCV) which measures "the amount of (money) income he would have to lose in order to offset the gain due to the fall in price".⁸³ In order to assess this quantity a line is constructed with the slope of the new budget constraint, MX_4 , tangent to indifference curve I at point C. If the individual's income is reduced by the amount $B B_1$ while maintaining the new price P_2 , he will be attaining the same level of satisfaction (represented by indifference curve I) at C as he was at A. The amount $B B_1$ is therefore a monetary measure of the amount of income required to just offset the gain due to the fall in price. In essence, this amount is the Hicksian PCV measure of consumer's surplus resulting from the decrease in the price of X.

The price-equivalent variation (PEV) is the second measure of consumer's surplus developed by Hicks. PEV measures "the gain in income which, if experienced without the price falling, would make the consumer as much better off as he is made by the fall in price without a change in money income".⁸⁴ In order to determine this quantity a line is constructed with the slope of the original budget line, MX_3 , tangent to indifference curve II at point D. If the individual's income is increased by the amount $A A_1$ while maintaining the original price P_1 , he will be attaining the same level of satisfaction (represented by indifference curve II) at D as he was at B. The amount $A A_1$ is therefore the monetary measure of the amount of income he would have to acquire in the absence of a price decrease to be equally satisfied. This amount is thus the Hicksian PEV measure of consumer's surplus resulting from the decrease in the price of X. It should be noted that the PCV for a given price decrease is exactly equal to the PEV for the alternate price increase and vice versa.⁸⁵

Recognizing that the PCV measures the change in income required to offset the change in price and not the change in income required to offset the change in quantity resulting from a price change, Hicks developed a quantity-compensating variation (QCV). This concept may also be demonstrated with the aid of Figure 3. After the price decrease, consumption of X increases from X_1 to X_2 . If the individual's income were now reduced by an amount $B B_2$, he would still be able to purchase X_2 while maintaining the level of satisfaction associated with the original indifference curve I. The amount of $B B_2$ is therefore the monetary measure of the QCV.

The fourth and final measure of consumer surplus developed by Hicks is the quantity-equivalent variation (QEV). Analogous to the QCV, this method is concerned with income changes required to offset quantity changes. Specifically, QEV measures the income change required to attain a new level of satisfaction while maintaining the original quantity consumed. Given the original budget constraint MX_3 , the individual maximizes his utility at point A consuming X_1 units of X. If his income were now increased by an

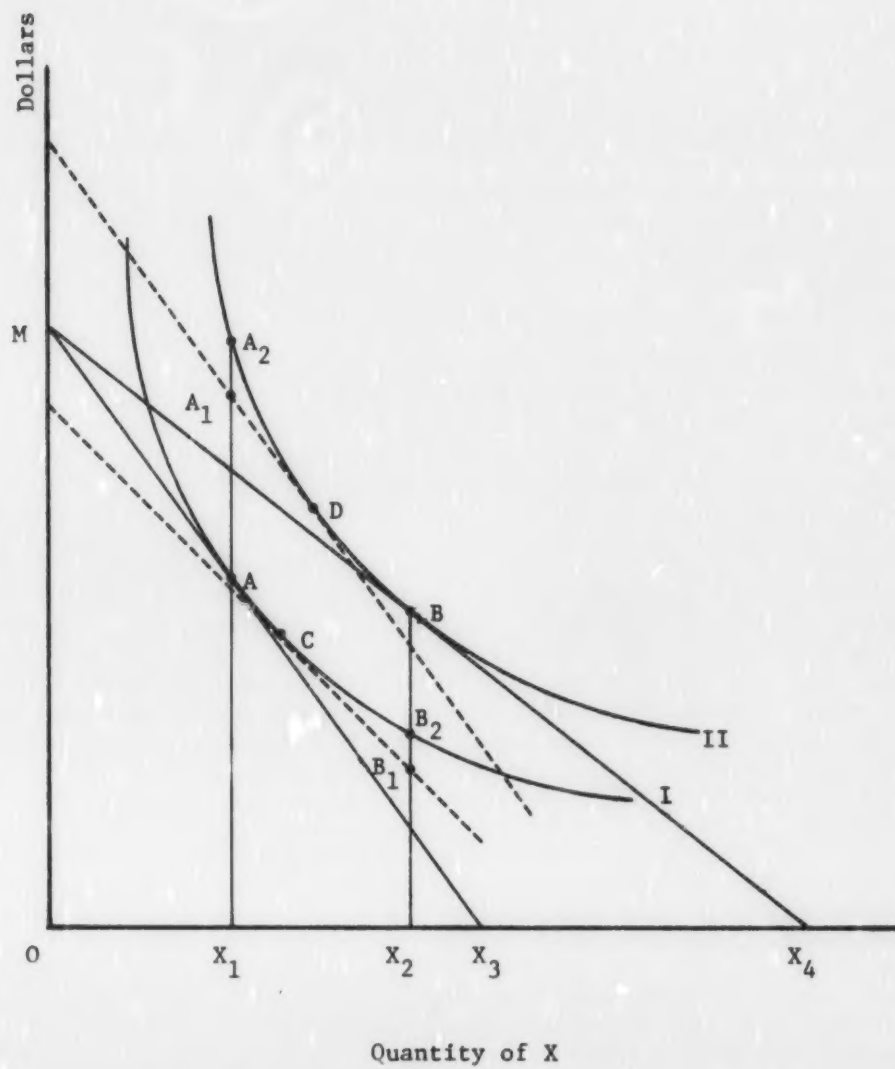


Figure 3. Hicksian consumer's surplus.

amount $A A_2$, he would still be able to purchase X_1 while attaining the level of satisfaction associated with the new indifference curve II. The amount $A A_2$ is therefore a monetary measure of QEV. It should be recognized that if the price changes are relatively small or the good in question composes a relatively small portion of the individual's budget, then all four Hicksian interpretations will result in virtually identical measurements equivalent to that obtained assuming a constant marginal utility of income.

In addition to overcoming the restrictive constant marginal utility of money assumption used by Marshall, Hicks demonstrated how real income (utility) changed with price changes. The Hicksian analysis also illustrated that consumers' surplus is a relative and not an absolute measure. That is, Hicks' analysis provides a monetary accounting for changes in utility and thus economic welfare changes resulting from price changes. Finally, it should be noted that for the minute changes in income expected to result from marginal changes in air quality, a more realistic assumption of a zero income effect results in all four Hicksian interpretations equalling the Marshallian measurement.⁸⁶

Recognizing that changes in welfare are contingent on changes in utility and that changes in utility can be measured via changes in consumer surplus, the similarity between the concept of a Pareto optimum or a Pareto efficient position for society and a position from which it is impossible to increase one person's consumer surplus without reducing that of another can readily be seen. In essence, this correspondence suggests the possibility of expressing the original criteria for the attainment of efficient resource allocation in terms of changes in consumer's surplus (CS).⁸⁷ That is, equality must exist between the marginal rates of substitution in consumption (MRS) between any two goods (e.g., a and b), and the marginal rates of transformation in production (MRT) between the same two goods:

$$MRS_{ab} = MRT_{ab} \quad (5)$$

Since the MRT_{ab} is simply equal to the ratio of the marginal social costs of a and b , this relationship may be expressed as:

$$MRS_{ab} = MSC_a / MSC_b \quad (6)$$

Winch (1971, p. 143) notes that the MRS between a commodity and money for an individual corresponds to his change in consumer's surplus (ΔCS) since his ΔCS represents the surplus of what he is willing to pay over that which he actually must pay. This relationship, combined with the conversion of good b to money (allowing b to correspond to all good except a), permits the re-writing of the efficiency criteria for a good as:

$$\Delta CS_a = MSC_a \quad (7)$$

When public goods are involved (e.g., clean air), however, this criterion is not directly applicable due to the exclusion principle; therefore as Samuelson (1969) notes, the relevant efficiency criterion becomes the equality of the sum of individual MRS and the MRT. Recognizing this relationship, the

efficiency criteria applicable to public good a must be written as:

$$\sum \Delta CS_a = MSC_a$$

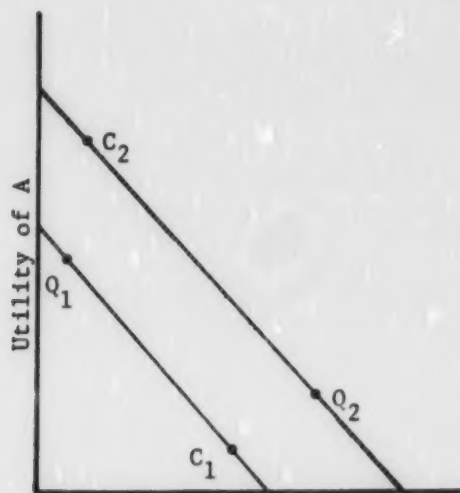
(8)

The possibility of applying this efficiency criterion to the analysis of non-Paretian changes (i.e., some individuals are made absolutely worse off while others are made absolutely better off) in public goods by summing individual's changes in consumer surplus⁸⁸ has received considerable attention. This concern arises because non-Paretian changes generate positive as well as negative changes in consumer's surplus. This summing estimates of consumer surplus appears to imply some type of interpersonal or normative comparison of utility since all individual changes in consumer's surplus are weighted equally in the summation procedure. The implied normative judgment that all individuals are to be treated equally is generally avoided by positive economists who contend that implied value judgments are outside the realm of economists. Since any new allocation scheme for the scarce resource clean air will be non-Paretian change, this concern is of central importance to the current effort of valuing the benefits of changes in human mortality resulting from improvements in ambient air quality. Essentially the problem of summing changes in consumer's surplus is analogous to comparing alternative welfare distributions since both involve evaluating changes in the relative positions of individuals. Economists have traditionally analyzed alternative welfare distributions in terms of the ability of the individuals who gain satisfaction to compensate those who lose satisfaction. The development of these compensation principles is the topic of concern in the following section.

Compensation Principles

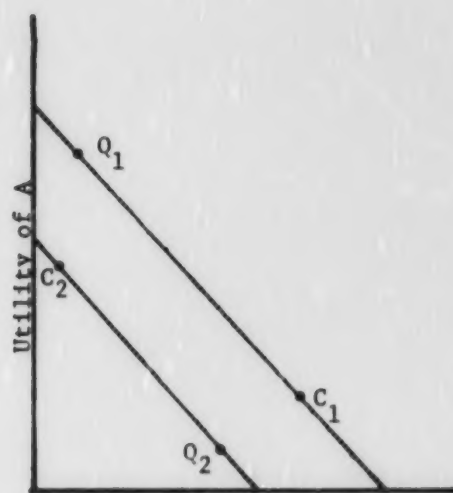
Barone in 1908 was the first economist to suggest that changes in an individual's welfare could be quantified in terms of the equivalent amount of income he would be willing to accept or pay in order to allow a return to his original welfare position. An expansion of this idea to the whole community forms the basic underlying structure of the Hicks-Kaldor compensation principle (H-K). Specifically, the H-K principle states that if a policy change results in some individuals being made better off while others are made worse off, welfare would be increased if the gainers could somehow compensate the loser so as to have them both better off. In the case of improvements in ambient air quality, this criterion may be restated in terms of consumer's surplus. If the sum of the positive changes in consumer's surplus resulting from a proposed policy change (i.e., an improvement in ambient air quality) exceeds the sum of any resulting negative changes in consumer's surplus, then social welfare could be improved by implementing the new policy. While neither Hicks (1939) nor Kaldor (1939) suggest that the actual compensation be paid, this issue as well as the possibility of paradoxical results have led to much debate and refinement concerning the compensation principle.⁸⁹

Utility possibility curves for a community of two individuals, A and B, before and after a proposed policy change intended to improve air quality are depicted in Figure 4.⁹⁰ These utility possibility curves will be used to demonstrate the application and development of the compensation principle. The Q_1 points on the $Q_1 C_1$ curves in each panel represent the utility



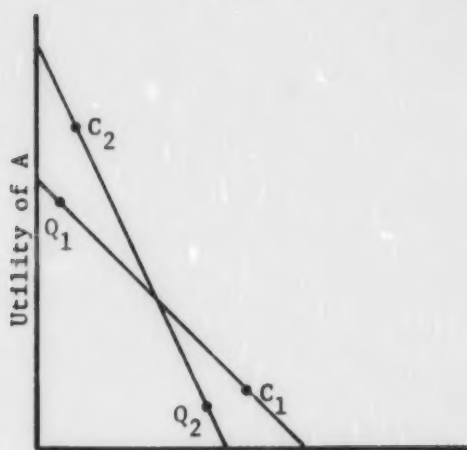
Utility of B

Case a



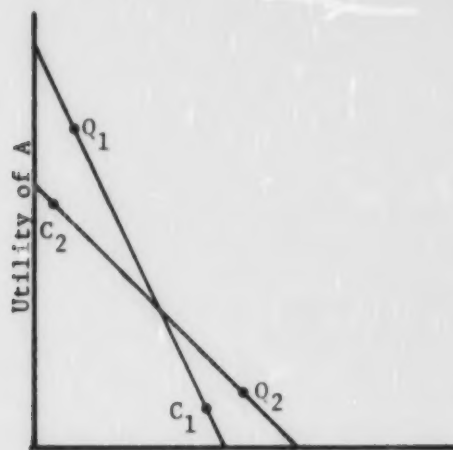
Utility of B

Case b



Utility of B

Case c



Utility of B

Case d

Figure 4. Utility possibility curves before and after air quality improvement.

levels attained by individuals A and B associated with the existing levels of air quality. All other points on these curves represent alternative possibilities which could be attained through alternative compensation schemes given existing policies (i.e., C_1). The Q_2 points on the $Q_2 C_2$ curves represent the utility levels attained by individuals A and B associated with air quality levels resulting from the proposed policy change. The other points on the $Q_2 C_2$ curves represent alternatives attainable through different compensation schemes given the new policy (i.e., C_2). In examples a through d, individual B benefits from the policy change since he moves to a higher indifference curve (i.e., B is the recipient of a positive change in his consumer's surplus), while individual A loses from the policy change since he moves to a lower indifference curve (i.e., A is the recipient of a negative change in his consumer's surplus).

Cases b and d, however, demonstrate instances where the H-K criterion is not fulfilled. Specifically, in neither of these cases may individual B sufficiently compensate individual A for his loss in a manner that will leave A minimally as well off as before the policy change. Therefore, regardless of whether compensation is actually paid, the proposed policy change in cases b and d may not unequivocally result in an improvement in social welfare. In fact, if the policy change in case b were implemented, the H-K criterion would be satisfied by reversing the policy alteration. Specifically, a policy change resulting in a movement from Q_2 to Q_1 would unequivocally increase social welfare after allowing individual A (recipient of the positive change in consumer's surplus) to compensate individual B (recipient of the negative change in consumer's surplus) in a manner capable of moving to a point on the $Q_1 C_1$ curve to the northeast of Q_2 (e.g., point C_1).

Cases a and c demonstrate instances where redistribution from Q_2 to C_2 would represent sufficient compensation by the gainer (individual B) to the loser (individual A) so as to leave both parties better off after the policy change.

Upon further examination, however, case c leads to a rather interesting result. If Q_2 was the original position and Q_1 the new position, a movement from Q_1 to C_1 would result in sufficient compensation to allow both parties to be better off. Thus, in case c using the H-K criterion, although a policy change resulting in a movement from Q_1 to Q_2 increases social welfare after allowing for compensation; a movement from Q_2 to Q_1 will also lead to an increase in overall welfare after allowing for compensation. This paradox was first noted by Scitovsky (1941) leading him to advocate a double test criterion for welfare improvement. Scitovsky contends that potential increases in welfare resulting from policy changes can unequivocally be claimed as an actual welfare improvement only if the H-K test before the policy change show no points superior to those after the change. That is, unequivocal statements concerning social welfare improvements may only be asserted in the absence of reversal patterns similar to case c.

Little accepts similar compensation criteria but also poses an additional criterion that potential redistribution is not a sufficient basis for making unequivocal statements on welfare improvement. Specifically, Little asserts that "an economic change is desirable (and increases welfare) if it causes a

good redistribution of wealth, and if the potential losers could not profitably bribe potential gainers to oppose it".⁹¹ Thus, in order to fulfill this criterion the resulting position after implementing the policy change must actually be socially preferred to the position before the policy change. Without any a priori information on social preferences, the only way policy changes can unequivocally result in welfare improvements is if the redistribution results in the attainment of a position to the northeast of the original utility possibility point. Thus, the evaluation of any policy change must be made on the basis of both its efficiency aspects (i.e., the Scitovsky modified H-K criterion) and its equity or distributional aspects. While these criterion may appear restrictive, it must be recognized that most individual policies only minutely modify the existing income distribution. As Krutilla suggests:

The relative magnitude of the redistribution associated with . . . decisions for which benefit-cost expenditure criteria have been traditionally employed will be of the second order of smalls in terms of its implications for measuring the change and, for practical purposes, can be ignored. (1964, p. 228)⁹²

Hence, as Mishan notes:

The possibility of such a reversal [the Scitovsky paradox] actually occurring in the real world, where there are a large number of goods and people, is much smaller, however, than the impression conveyed by a two good two-person diagram. (1973, p. 321)⁹³

Therefore, as long as the redistributational aspects of a policy change are this small, cost-benefit analysis may concentrate on the estimation of changes in society's welfare without regard to modifications in the distribution of welfare among individuals.

It has now been demonstrated that cost-benefit analysis has its fundamental roots in theoretical economics. Whether this link is "the basis of . . . all economics" as stated by Haveman and Weisbrod⁹⁴ or a "dilluted version of . . . allocation theory"⁹⁵ is not of major importance. What is of paramount concern is the existence of a consistent conceptual framework composed of the concept of consumer's surplus and the compensation principle within which cost-benefit analysis must be performed. In essence, the basic objective of cost-benefit analysis may be summarized as the maximization of the present value of net social benefits. Benefits can now be defined as those results of a policy change that generate positive changes in consumer surplus or cost savings (increases in welfare) while costs include those results which generate negative changes in consumer surplus or increased costs (decreases in welfare). The objective of the following section is to examine the application of cost-benefit analysis in determining the optimum level of air quality.

COST-BENEFIT ANALYSIS--THE APPLICATION

While traditional applications of cost-benefit analysis have involved public investment projects, the term "project" can be applied more generally to include proposed changes in laws, regulations, and various tax-subsidy schemes.⁹⁶ For present purposes, the "project" is the attainment of an optimal use of the scarce air resource. That is, given the alternative uses of the air (e.g., waste-assimilation, life-support), what level of air quality represents an optimal allocation of clean air between these uses? The following statement by Krutilla synthesizes the arguments developed earlier for the use of cost-benefit analysis in the treatment of this problem:

Essentially, a private cost-gains calculus is employed in deciding private firms' policies; externalities and other divergences between private and social product are neglected. Benefit-cost analysis, on the other hand, seeks to take account of such divergences as a basis for guiding public action either when market prices do not actually reflect social value or when, by virtue of the individual's nature of collective goods, no market exists from which to observe directly objective evidence of the community's valuation of the social marginal product.⁹⁷

In examining the theoretical foundations underlying the application of cost-benefit analysis, it was demonstrated that the efficiency criterion could be stated in terms of dollar values.⁹⁸ Specifically, the optimum level of air quality was attained when the sum of the changes in individual's consumer surplus resulting from increases in ambient air quality equaled the marginal social costs (MSC) of attaining that level of air quality. By grouping all benefits and costs, this criteria may be restated as:⁹⁹

$$MSC = MSB$$

where MSB is equal to marginal social benefits.

Attempts at single, all encompassing, estimates of air pollution costs to society (i.e., the benefits of pollution abatement) have been conducted primarily through the analysis of property value differentials.¹⁰⁰ The advocates of this approach contend that:

If the land market were to work perfectly, the price of a plot of land would equal the sum of the present discounted streams of benefits and costs derivable from it. If some of its costs rise (e.g., if additional maintenance and cleaning costs are required), the property will be discounted in the market to reflect people's evaluation of these changes. Since air pollution is specific to locations and the supply of locations is fixed, there is less likelihood that the negative effects of pollution can be significantly shifted onto other markets. We should therefore expect to find the majority of effects reflected in this market, and can measure them by observing associated changes in property values.¹⁰¹

Although property markets do not function perfectly, property value differentials may reflect many of the social costs resulting from air pollution. It is unrealistic, however, to expect consumers to completely discount such costs if their existence is not generally recognized (e.g., health costs).

In an attempt to partially account for these costs, estimates have been made of the effects of air pollution on human health,¹⁰² materials,¹⁰³ vegetation,¹⁰⁴ and other aspects.¹⁰⁵ Using effect-specific dose-response estimates (the effects of alternative levels of pollution), it is also possible to calculate the MSB of pollution abatement. This approach requires a careful summation of the various effect-specific benefit functions (e.g., human health, vegetation) to determine society's overall marginal benefit function for air quality improvements. Equating this inclusive MSB function with the inclusive MSC for improving air quality will result in the attainment of the socially optimum level of air quality. This approach is illustrated using the hypothetical marginal social benefit curves depicted in Figure 5. Specifically, MSB_H , MSB_M , MSB_V , and MSB_O represent the hypothetical MSB curves for health, materials, vegetation, and all other dose-response relationships, respectively. The summation of these individual MSB is represented by the curve labeled MSB. The optimum level of air quality is where the MSB curve intersects the hypothetical MSC curve or X_E . At any point to the left of X_E , the social gains from a marginal increase in air quality exceed their costs, indicating that society can experience a net increase in welfare by attaining the next higher level of air quality. For points to the right of X_E , the social costs of an additional unit of air purity exceed the value of the changes in social benefits; therefore, no further increase in air quality is socially desirable. Any increases in air purity beyond X_E would in fact decrease social welfare.

While empirical estimates of the hypothetical MSB curves depicted in Figure 5 have been calculated, severe difficulties are encountered when attempting to empirically determine the optimum level of air quality. In particular, the efforts to quantify the MSB are greatly complicated by problems of isolation and valuation in monetary units of air pollution's many potential effects. The MSC, while not simple to calculate, are substantially less difficult to estimate since measurements primarily involve direct dollar costs rather than estimates of consumer surplus. Therefore, economists have concentrated on estimating the benefits of pollution abatement. Following this precedent, the remainder of this present effort will focus solely on properly monetarizing the social costs of pollution-induced mortality estimated in Section IV. The reasons for this concentration are threefold. First, Section 109 of the Air Quality Act of 1967 requires the establishment of primary air quality standards "to protect the public health." Second, there exists substantial debate on the issue of ambient air quality's aggravation effect on mortality, particularly at daily exposure levels. Finally, prior quantification of these costs has been consistent with the underlying assumptions of cost-benefit analysis.¹⁰⁶

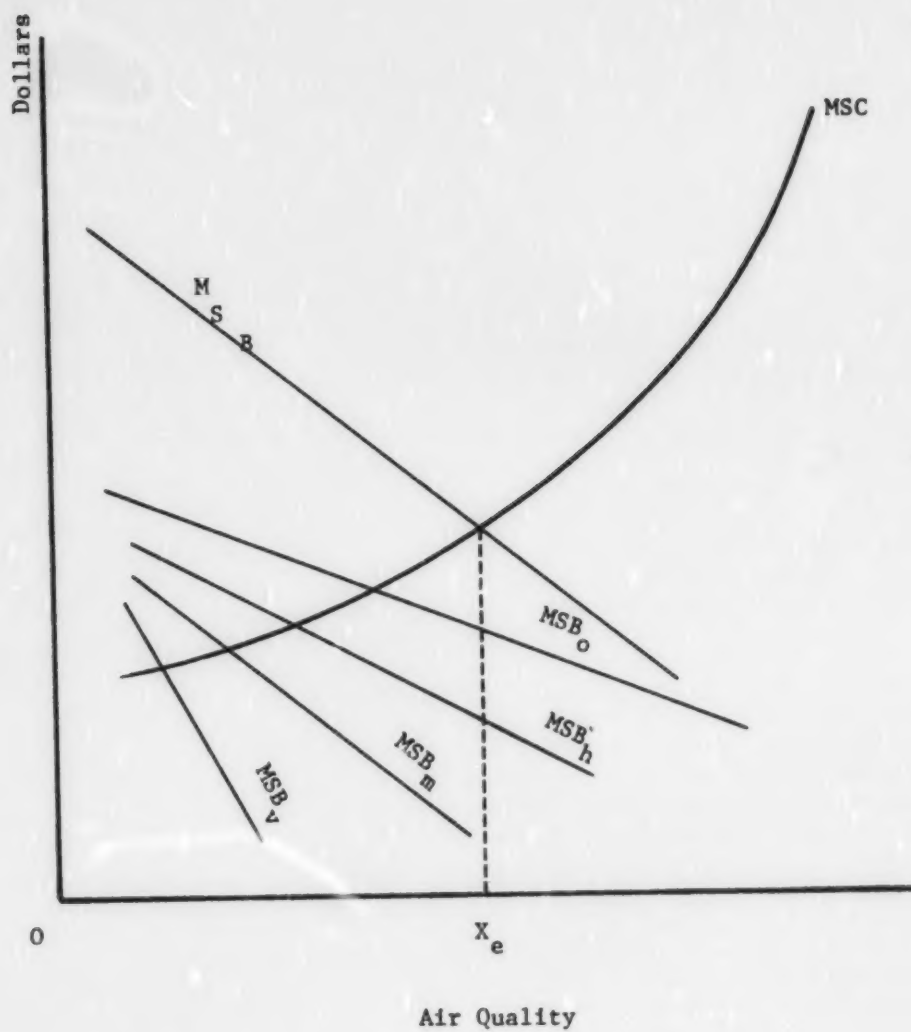


Figure 5. Marginal air pollution costs and benefits.

SECTION VI
EVALUATION OF MORTALITY BENEFITS: MONETIZATION OF
DECREASES IN MORTALITY

Section IV has provided estimates of physical social benefits, measured as potential decreases in mortality, that can be expected from improvements in air quality. The present section will review and evaluate methods for quantifying these benefits in dollar terms. Specifically, the various procedures for monetizing changes in probabilities of death will be reviewed for consistency with the Paretian basis of cost-benefit analysis as outlined in the preceding section. Finally, the most theoretically precise empirical estimates currently available will be applied to the mortality functions estimated in Section IV in order to monetize the mortality component of the total marginal social benefit function.

SPURIOUS MONETIZATION PROCEDURES

Thus far, most attempts at monetizing changes in life expectancy (mortality) have been inconsistent with the Paretian basis of cost-benefit analysis. In general, these approaches have focused on either the incorrect measure (e.g., lives rather than probability of death) or valuation of life or both. Some economic studies have even attempted to boldly answer the philosophical question--What is the value of life?

Four broad classifications of such spurious monetization procedures can be identified; (1) present value of future earnings; (2) net present value of future earnings; (3) the insurance principle; and (4) governmental decisions.¹⁰⁷ Each of these procedures will be evaluated for consistency with the theoretical basis of cost-benefit analysis. The reason for this type of comparative evaluation is that when properly utilized, cost-benefit analysis can provide an efficient means of collectively allocating scarce resources. Specifically, this section will demonstrate why each of these four monetization procedures is incorrect for assessing what individuals are willing to pay for welfare improvements or decreases in mortality.

Present Value of Future Income

One of the most commonly used methods of estimating the value of mortality changes is based on the present value of future income (PVY).¹⁰⁸ When applied to mortality rate changes, this approach involves a two-step procedure. First, calculate the PVY for an average expected stream of future income using the following formula:

$$PVY = \sum_{N=1}^D Y_N P_N (1-r)^{-(N-1)} \quad (9)$$

where:

PVY = present value of future income

N = the year

Y_N = average expected income in year N

P_N = probability of surviving through year N

r = time discount factor.

The PVY is then multiplied by the expected number of lives to be saved in order to obtain an estimate of the social value resulting from a decrease in mortality.

The principal objection to this approach is that it addresses the question of how much a person contributes to material economic activity rather than what individuals are willing to pay for decreases in their probability of death or how much individuals must be compensated to assume higher probabilities of death. Another criticism concerning the use of PVY to monetize the welfare changes resulting from changes in mortality rates is that such an approach leads to the conclusion that for certain groups of people (e.g., retired individuals and housewives) it may not be worthwhile to reduce their probabilities of death.¹⁰⁹ Rice and Cooper (1967), for example, using 1964 data and a 4 percent time discount factor estimated a PVY of \$136,121 for white males twenty-five to twenty-nine, but only a PVY of \$396 for nonwhite males over eighty-five. Using these results, it can incorrectly be inferred that white males in the twenty-five to twenty-nine age group should be compensated approximately 340 times the rate of nonwhite males over eighty-five for a change in welfare resulting from a given increase in their probability of death. This result, however, bears no relationship to changes in the individual's consumer surplus. In essence, this approach disregards the individual's own valuation as well as that of others (e.g., family and friends) and hence, PVY is inconsistent with the theoretical basis of cost-benefit analysis.

It should be recognized that these criticisms do not imply that PVY is irrelevant to the correct evaluation of changes in mortality. As Schelling notes:

Discounted lifetimes earnings are relevant only in the way that they are relevant to ordinary decisions about consumption, saving, quitting a job or buying a house. They are part of the income and wealth data that go into the decisions. Their connection is a functional one, not an accounting one.¹¹⁰

Net Present Value of Future Earnings

Another spurious method for evaluating mortality reductions is the PVY net of the individual's own consumption (NPVY).¹¹¹ This approach was originally designed by Dublin and Lotka (1946) to determine how much insurance an individual should maintain in order to avoid undue economic hardship on his family in the event of an untimely death. Most of the criticisms of this approach are identical to those of PVY. In addition, however, this technique also may lead to the conclusion that individuals with small or negative NPVY (e.g., individuals on welfare, retired persons and housewives) have little or no economic value to society. Carried to an extreme, this approach may even result in an "economic" justification for genocide.

Insurance Principle

Another monetizing technique is based on the life insurance premium an individual pays and the probability of dying. If, for example, an individual pays \$100 annually for life insurance and his probability of death is 0.001, then the individual values his life at \$100,000. This estimate is invalid on several grounds. First, the \$100 is only a minimum estimate, since an individual may be willing to pay in excess of the \$100 premium. Second, an individual is not securing any change in his probability of death (increases in welfare), only purchasing insurance for family security. While a single individual may not purchase life insurance, he probably is willing to pay for a decrease in his probability of death and certainly should be compensated for increased risks of death imposed on him. This measure reflects neither of these likelihoods, and, therefore, the insurance principle cannot be used as a surrogate for willingness to pay for increases in life expectancy.

Governmental Decisions

The final spurious monetizing technique is based on analysis of governmental decisions. The advocates of this approach contend that society evaluates mortality changes daily in the form of governmental decisions on safety. If such decisions were drastically at odds with the evaluation of their constituency, then government decision makers would not be reelected. While this approach may appear to reflect social willingness to pay for mortality reductions, this conclusion is not valid since:

- [1] decisions to invest in certain projects are not determined by popular vote; . . .
- [2] investment decisions are not motivated primarily by the desire to advance the general welfare; . . .
- [3] an implicit value attributable to loss of life by a particular public programme will differ widely from an implicit value derived from another public programme.¹¹²

Moreover, Usher has demonstrated that using this approach governmental safety decisions are inconsistent when extrapolated from the base level risk (e.g., one in a million reduction in probability of death) to "certain death."¹¹³ Specifically, Usher has shown the existence of wide ranging estimates from the \$37,000 recommended by the National Safety Council for use in cost-benefit analysis to \$4,500,000 extrapolated from the decision to produce a special ejector seat in a jet plane. The examination of these governmental decisions, therefore, cannot be expected to reveal society's willingness to pay for decreases in mortality.

THE CORRECT CONCEPTUAL MEASURE

The theoretical inconsistencies between the four previous monetizing techniques and the theoretical basis of cost-benefit analysis have been recognized by Schelling (1968), Usher (1973), Mishan (1973) and others (e.g., Hirshleifer, *et al.*, 1974 and Zeckhauser, 1975). As stated earlier, consistency with the foundations of cost-benefit analysis requires that changes in welfare be expressed as either the compensation required to return an individual to his original utility level (or bundle of goods) after a decrease in welfare or as willingness to pay in order to maintain an increase in welfare. Specifically, if an improvement in air quality reduces mortality, the correct social valuation of this benefit is the summation of the resulting positive changes in consumer surplus or the summation of what individuals would be willing to pay rather than forego this increase in welfare. Alternatively, if a reduction in ambient air quality leads to increases in an individual's probability of death, then the correct social valuation of these costs is the summation of the resulting negative changes in consumer surplus or the summation of what individuals would require in compensation to regain their original level of welfare.

This type of approach to the evaluation of changes in mortality for an individual consumer can simplistically be depicted with the aid of the indifference map in Figure 6. In this figure, income (or all other goods) is represented on the vertical axis while the individual's probability of life (one minus the mortality rate) is depicted on the horizontal axis. If an individual is originally receiving income Y_0 and experiencing a probability of life of X_0 , his welfare position is expressed by indifference curve I. If ambient air quality improves such that his probability of life increases from X_0 to X_1 , this change in welfare is expressed by the movement from indifference curve I to indifference curve II. The relevant dollar valuation now becomes the amount of income the individual would be willing to give up in order to maintain this new higher probability of life (X_1) or the amount of money he would have to lose in order to offset the gain in his utility due to the decrease in his mortality rate. This amount is equal to BC since the individual would be just as well off (indifference curve I) at the new lower mortality rate as before.¹¹⁴

The summing of BC, or its equivalent, for all members of society should then provide an estimate of the total benefit received by all individuals from a reduction in their own mortality rates resulting from an improvement in ambient air quality. This amount, however, is not the total social benefit resulting from the air quality improvement. In addition to benefits in the areas of public health, material preservation and vegetation growth there also

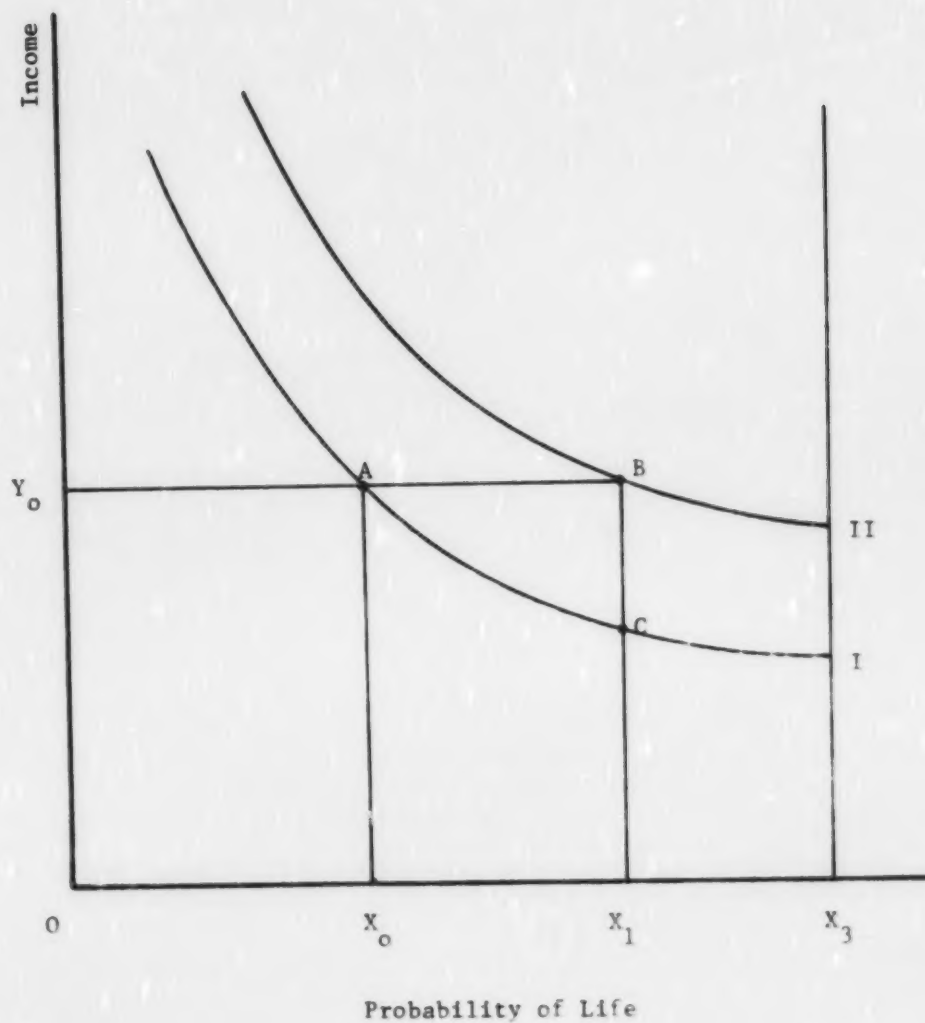


Figure 6. Individual's indifference map for risk and income.

exists benefits to friends, family and society from decreases in the individual's probability of death. Specifically, friends and family gain by enjoying the individual's comradeship longer and also there is the potential gain to society in the form of extra output generated from a reduction of any individual's probability of death.¹¹⁵ Thus, the relevant social benefit from a reduction in any individual's probability of death is the sum of what he, his friends and relatives, and society are willing to pay rather than forego the reduction. Summing these valuations for all individuals in society, the total social benefit for any change in mortality can be estimated.

Now that the concept of consumer's surplus (willingness to pay) has been theoretically applied to the valuation of changes in mortality, the relevant question becomes whether reliable empirical estimates of this theoretical construct can be obtained. The possibility of simply asking individuals what they are willing to pay for changes in their probability of death or that of friends and relatives is the logical starting point. There are, however, serious problems inherent with this approach. First, individuals may not express their true willingness to pay because of the free rider problem evolving from the inapplicability of the exclusion principle to the public good air. Second even if individuals would express their valuation, most of the probabilities usually discussed are relatively small (e.g., one in a million), and it has been argued that individuals cannot adequately assess such minute probabilities.¹¹⁶ In an attempt to circumvent these problems, economists have focused on the market system to explore the possibility that individuals reveal monetary valuations of changes in their own probability of death by actually trading such probabilities for changes in money income. If such activity does occur, then it should be possible to ascertain the values revealed. Fortunately, such a market reflection does exist in the form of explicit or implicit premiums paid to various occupations for assuming extra risk. These risk premiums may be in the form of direct income or indirect compensation (e.g., pension benefits). There are, however, difficulties involved with the use of these premiums, most of which have been well stated by Zeckhauser:

The logical problem is that the people who are assuming the risks are those who value them the least in relation to the benefits they get for risking them. They may be the poor, they may be the people whose probability assessments are most in error, they may be the people who legitimately have the lowest probability of being injured, they may be the people who will die soon anyway, or they may be the people who value their own lives the least highly.¹¹⁷

In addition to these considerations is the belief that individuals will seldom accept any monetary payment in exchange for the certainty of death. Therefore, complete¹¹⁸ extrapolation from observed values to "the value of a life" is impossible.

In light of these criticisms, market reflections of compensation required to induce an individual to accept additional risk must always be qualified. Specifically, since such estimates only approximate one of the components of society's total valuation, any extrapolation of these results to the

monetization of the benefits of decreases in mortality resulting from improvements in ambient air quality must be interpreted as an extreme lower-bound estimate. Following Mishan, however, it may be argued that "there is more to be said for rough estimates of precise concepts than precise estimates of economically irrelevant concepts".¹¹⁹ Applying Mishan's reasoning to obtaining estimates of willingness to pay for decreases in the probabilities of death, the labor market may be viewed as a reflection, however imprecise, of the economically precise concept.

Figure 7 graphically depicts how the labor market reflects individual's monetary valuation of risk changes. Specifically, this figure shows how an individual can increase his welfare by rationally choosing between changes in risk and corresponding changes in compensation or payment. For example, assume an individual at point A has the opportunity to gain income by increasing his risk. If his trade possibilities are summarized by MM' , the market equilibrating trade-off curve between risk and income, he will maximize his welfare by trading income for security and move from A to B. The monetary value of this change in his welfare is BC, the Hicksian QCV. What is observed in the labor market, however, is the income differential Y_0Y_1 which is larger than BC since the marginal utility of money is not constant. Using the trade possibility curve MM' , the marginal value of this market reflection of the compensation required to induce the individual to assume the small increase in his probability of death may be expressed as $-dy/dx$ or Y_0Y_1/X_0X_1 . Extrapolating this marginal valuation to the individual's valuation of life (e.g., OM) may not be valid if the individual has a high probability of death (low probability of life) beyond which he will not make income-risk trade-offs. This possibility is demonstrated in Figure 7 by the vertical line extending from the low probability of life X. As Hirshleifer notes: "Willingness to make small or 'marginal' adjustments at this rate of exchange does not by any means imply willingness to make large adjustments at the same terms."¹²⁰

Recalling that air pollution-induced mortality changes are small (at least for the ambient concentrations typically found in Allegheny County),¹²¹ marginal approximations of the Hicksian QCV will therefore suffice for estimating the dollar amount that individuals would be willing to pay for decreases in their mortality rates (the Hicksian QEV) resulting from increases in ambient air quality. Indeed, it should be recalled that the Hicksian QCV of a price rise (increase in risk) is the mirror image of the Hicksian QEV of a price fall (decrease in risk). Thus, the assignment of these dollar values to changes in the mortality rates associated with improvements in ambient air quality can be made, provided that dollar estimates consistent with this theoretical interpretation can be found.

DOLLAR ESTIMATES OF SOCIAL BENEFIT

The gap between an acceptable theoretical determination of the willingness of individuals to pay for decreases in mortality and quantification of the abstract model is quite large. Fortunately, recent work by Thaler and Rosen (1973) has managed to obtain valid empirical estimates of the marginal valuation curve (MM' in Figure 7).

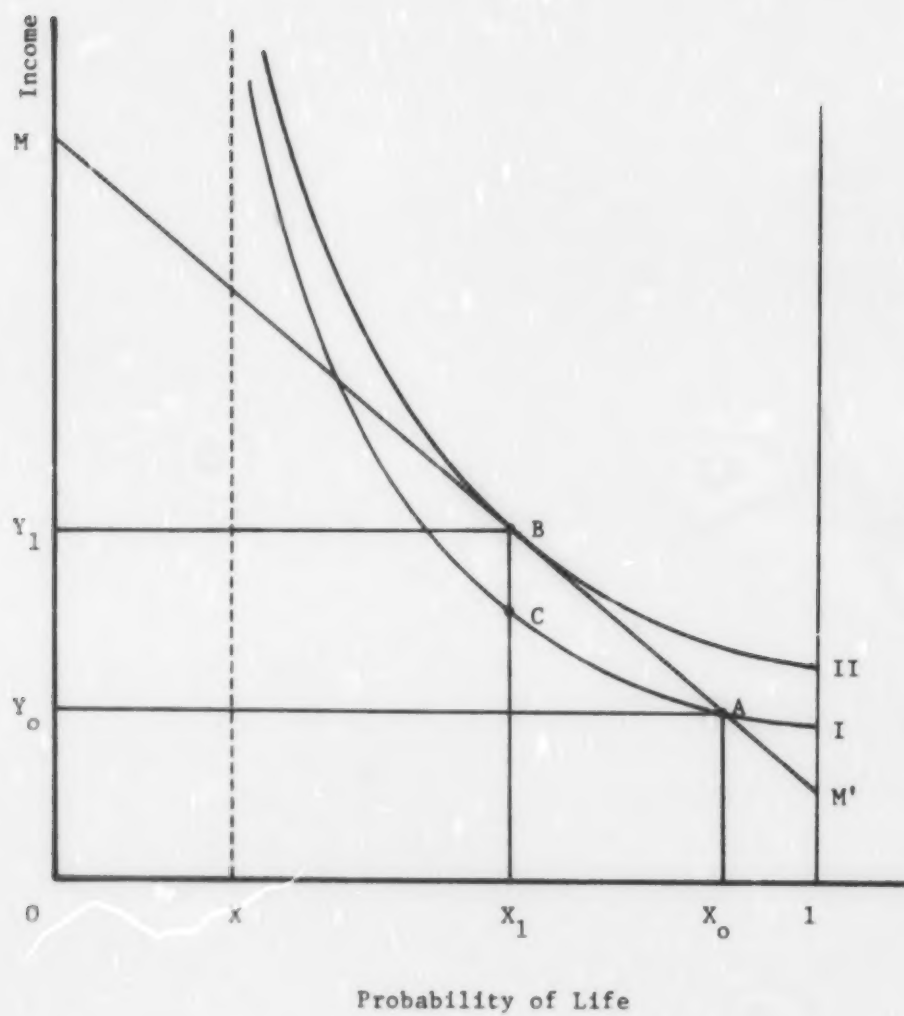


Figure 7. Market reflection of risk-income trade-off.

By matching risk data which detailed the number of excess deaths by industry and occupation from the 1967 Occupation Study of the Society of Actuaries with the 1967 Survey of Economic Opportunity data on personal and industrial characteristics of individuals, Thaler and Rosen were able to construct a data base consisting of 907 adult male heads of household. The means and standard deviations of their variables are presented in Table 9. Using this data, the authors statistically controlled for "other" factors in addition to risk which influence wage rates. Specifically, regional, demographic, social and job characteristic differentials were controlled for by fitting various hedonic demand curves to this data through the use of multiple regression analysis. Utilizing this technique, Thaler and Rosen were able to estimate a set of implicit marginal prices for risk acceptance. The results of their regression analysis, both linear (part A) and semi-log (part B) are presented in Table 10. The reason for the presentation of two functional forms is that their data did not "provide enough resolution on functional form to make a choice".¹²²

The coefficients presented in Table 10 (parts A and B) are estimates of the wage equation assuming that "all the non-risk variables . . . simply shift the wage-risk relationship leaving its slope intact".¹²³ Recalling from Table 9 that the risk variable has been scaled by a factor of 10^5 , the estimated risk coefficient 0.0352 in equation one part A indicates that individuals will accept an increased probability of death equal to 0.001 for an extra \$3.52 per week.¹²⁴ Assuming a fifty-week working year, this estimate translates to an annual risk premium of \$176 for an increase of 0.001 in an individual's probability of death.

Equation two in part A replaces the occupational dummy variable with social economic status (SES) dummy variables. In this equation, the estimated coefficient 0.0520 indicates that individuals will accept a 0.001 increase in their probability of death for an extra \$5.20 per week of \$260 per year. Corresponding estimates for equations one and two of Table 10 part B (semi-log) estimated at the mean are somewhat smaller than those of part A (linear). Equation one of the semi-log form implies an annual risk premium of \$136 for the 0.001 increase in probability of death while equation two implies an annual premium of \$189. Extrapolating these marginal values to the point of a "statistical death" their estimates "lie in a reasonably narrow range of about \$200,000 $\pm$ 60,000".¹²⁵

Before proceeding to use these results to quantify in dollar terms the benefits of air quality-related mortality reductions, it should be noted that these risk premiums contain an inherent bias. Specifically, as demonstrated in Table 11, Thaler and Rosen's sample was composed of relatively risky occupations. Therefore, the individuals included in the sample were relatively less risk averse than the general population. This downward bias coupled with the fact that these risk premiums only approximate the individual's own willingness to pay for risk reductions and not those of family, friends and society insure that any benefit estimates based on the Thaler and Rosen results will unequivocally represent a lower bound estimate.

TABLE 9. MEANS AND STANDARD DEVIATIONS OF THE VARIABLES
INCLUDED IN THALER AND ROSEN'S WAGE FUNCTIONS*

Variable	Mean	Standard Deviation
<u>Dummy Variables**</u>		
Urban	.69	.46
Northeast	.28	.45
South	.29	.45
West	.17	.38
Family size exceeds two	.76	.42
Manufacturing industry	.24	.42
Service industry	.58	.49
Worker is white	.90	.30
Worker employed full-time	.98	.10
Worker belongs to union	.45	.49
Worker is married	.92	.26
Occupation is operative	.27	.44
Occupation is service	.45	.49
Occupation is labor	.22	.42
<u>Continuous Variables</u>		
Age (years)	41.8	11.3
Education (years)	10.11	2.73
Weeks worked in 1966	49.4	5.4
Hours worked last week	44.9	11.6
Risk (probability x 10 ⁵)	109.8	67.6
Weekly wage (week prior to survey)	\$132.65	50.80

*Source: Thaler and Rosen (1973).

**The mean of the dummy variables is proportion in sample with the designated characteristic.

TABLE 10. THALER AND ROSEN REGRESSION ESTIMATES OF WEEKLY WAGE RATES*
Part A. Linear

Independent Variables	Equation (1)	Equation (2)
Risk	.0352 (.0210)**	.0520 (.0219)
Urban	13.80 (4.2)	15.71 (2.95)
Northeast	-3.71 (3.65)	-4.29 (3.67)
South	-8.86 (3.70)	-8.90 (3.74)
West	9.13 (4.13)	10.50 (4.18)
Age	3.89 (0.80)	3.81 (0.83)
(Age) ²	-.0479 (.0092)	-.0468 (.0097)
Education	3.40 (0.55)	3.27 (2.40)
(Education) ²	-	-.021 (.128)
White	22.92 (4.53)	22.93 (4.50)
Union	25.5 (3.25)	27.16 (3.25)
Full-Time	-1.63 (12.9)	-.86 (12.6)
Hours Worked	1.50 (.12)	1.41 (.12)
Occ 1 Operative	-18.7 (9.2)	-
Occ 2 Service Worker	-24.6 (9.5)	-
Occ 3 Laborer	-25.6 (13.4)	-
SES 1	-	4.68 (5.17)
SES 2	-	-17.17 (3.34)
SES 3	-	-20.69 (5.53)
R ²	.41	.41

*Source: Thaler and Rosen (1973).

**Standard errors are in parentheses.

TABLE 10. THALER AND ROSEN REGRESSION ESTIMATES OF WEEKLY WAGE RATES*,+
Part B. Semi-Log

Independent Variables	Equation (1)	Equation (2)
Risk	.000206 (.000167)**	.000286 (.000174)
Urban	.114 (.033)	.132 (.024)
Northeast	-.00357 (.0029)	-.00373 (.0291)
South	-.0623 (.0295)	-.0568 (.0298)
West	.0857 (.0327)	.0974 (.0332)
Age	.0381 (.0063)	.0385 (.0063)
(Age) ²	-.000469 (.000073)	-.000475 (.000077)
Education	.0332 (.0044)	.0531 (.0190)
(Education) ²	-	-.00129 (.00101)
White	.228 (.036)	.228 (.036)
Family Size - 2	-	-.00204 (.0274)
Union	.203 (.026)	.214 (.025)
Full-Time	.275 (.103)	.303 (.101)
Hours Worked	.0113 (.00096)	.0105 (.00095)
Occ 1 Operative	-.0885 (.0728)	-
Occ 2 Service Worker	-.126 (.075)	-
Occ 3 Laborer	-.218 (.106)	-
SES 1	-	.0152 (.0411)
SES 2	-	-.128 (.026)
SES 3	-	-.194 (.047)
R ²	.47	.46

*Source: Thaler and Rosen (1973, p. 35).

**Standard errors are in parentheses.

+Dependent variable is the log of the weekly wage rate.

TABLE 11. THALER AND ROSEN'S SAMPLE OCCUPATIONS AND RISKS*

Occupation	Risk**	Occupation	Risk**
Fishermen	19	Switchmen	152
Foresters	22	Taxicab drivers	182
Teamsters	114	Truck drivers	98
Lumbermen	256	Bartenders	176
Mine operators	176	Cooks	132
Metal filers, grinders and polishers	41	Firemen	44
Boilermakers	230	Guards, watchmen and doorkeepers	267
Cranemen and derrickmen	147	Marshals, constables, sheriffs and bailiffs	181
Factory painters	81	Police and detectives	78
Other painters	46	Longshoremen and stevedores	101
Electricians	93	Actors	73
Railroad brakemen	88	Railroad conductors	203
Structural iron workers	204	Ships' officers	156
Locomotive firemen	186	Hucksters and peddlers	76
Power plant operatives	06	Linemen and servicemen	02
Sailors and deckhands	163	Road machine operators	103
Sawyers	133	Elevator operators	188
		Laundry operatives	126
		Waiters	134

*Source: Thaler and Rosen (1973, p. 30).

**Units of measure are extra deaths per 100,000 policy years.

By selectively combining the average marginal compensation for risk-estimates ($0.001 = \$200$) derived from the Thaler and Rosen analysis with the various age-sex-specific pollution-related mortality functions estimated in Section IV, it is now possible to monetize the pollution-aggravated mortality component of the marginal social benefit function. The resulting dollar estimates, unlike those traditionally employed in cost-benefit analysis of mortality reductions, will be consistent with the Paretian basis of cost-benefit analysis because such estimates will be based on changes in consumer's surplus. Specifically, the marginal compensation premiums estimated by Thaler and Rosen may be interpreted as estimates of the compensation required to offset a negative change in an individual's consumer surplus (e.g., acceptance of increased risk) which is equal to the amount he would be willing to pay rather than forego an equivalent positive change in his consumer's surplus (e.g., a reduction in risk). This equivalency was discussed in Section V

along with the development of the Hicksian concepts of consumer's surplus. The procedure used to combine the risk and mortality estimates involves the following four steps:

- (1) Estimate changes in the various pollution-related mortality rates for a 1 percent improvement in each of the air quality variables. This task was undertaken by using percentage changes around the mean values of SO_2 and TP while holding all other independent variables constant at their mean values. The results of these estimates for Allegheny County are presented in Table 12.

TABLE 12. CHANGES IN AGE-SEX SPECIFIC POLLUTION-RELATED MORTALITY RATES RESULTING FROM 1 PERCENT DECREASE IN SO_2 OR TP**

Sex	Age	SO_2	TP
Male	Less than 45	0.016	0.613
	45 - 64	0.618	4.924
	65 and over	0.384	12.614
Female	Less than 45	0.012	0.428
	45 - 64	0.100	1.924
	65 and over	1.016	11.661

*All mortality rate changes are per 100,000.

+All other variables held constant on their mean value.

- (2) Multiply these changes in mortality rates per thousand individuals by the Thaler and Rosen marginal compensation estimate of \$200. This results in an average marginal social benefit estimate for the various age-sex specific pollution-related mortality rate changes which is consistent with the Paretian basis of cost-benefit analysis. The results of these procedures are presented in Table 13.

TABLE 13. AVERAGE AGE-SEX-SPECIFIC MARGINAL ANNUAL DOLLAR BENEFITS
FOR POLLUTION-RELATED MORTALITY CHANGES RESULTING FROM
1 PERCENT DECREASE IN SO₂ OR TP*

Sex	Age	SO ₂	TP
Male	Less than 45	0.032	1.226
	45 - 64	1.236	9.848
	65 and over	0.768	25.228
Female	Less than 45	0.024	0.856
	45 - 64	0.200	3.848
	65 and over	2.032	23.322

*All figures are in 1970 dollars.

- (3) Multiply these average marginal social benefit estimates by the population at risk. This step involves multiplying the various age-sex values in Table 13 by the corresponding 1970 white population of Allegheny County in order to obtain estimates of the total age-sex-specific mortality benefits of pollution abatement. The results of these multiplications are presented in Table 14.

TABLE 14. TOTAL AGE-SEX-SPECIFIC MARGINAL ANNUAL DOLLAR BENEFITS
FOR POLLUTION-RELATED MORTALITY CHANGES RESULTING
FROM A 1 PERCENT DECREASE IN SO₂ OR TP*

Sex	Age	SO ₂	TP
Male	Less than 45	15	557
	45 - 64	205	1,636
	65 and over	<u>50</u>	<u>1,652</u>
	Total Male	270	3,845
Female	Less than 45	11	408
	45 - 64	38	638
	65 and over	<u>189</u>	<u>2,167</u>
	Total Female	238	3,213
Total Male and Female		508	7,058

*All figures are in thousands of 1970 dollars (\$1,000).

- (4) Sum the age-sex-specific total benefit estimates in Table 14 to obtain an estimate of the total benefits accruing to the residents of Allegheny County from decreases in mortality resulting from improvements in ambient air quality. The results of these summations are also presented in Table 14.

From the results presented in Table 14 it can be concluded that the benefits of reduced mortality derived from an abatement or particular matter are substantially higher than for sulfur dioxide abatement. That is, individuals in Allegheny County are willing to pay at least approximately \$7 million annually in order to maintain TP at a level 1 percent below those experienced during the 1968-1972 period but only \$.5 million annually for a similar percentage reduction in SO₂. These relative dollar differentials were to be expected on the basis of the results from the mortality model estimated in Section IV, especially, the elasticity estimates of Table 8, Part B.

It must be emphasized, however, that the relationships estimated in this chapter are designed as inputs in an overall cost-benefit analysis of air quality, and only relative conclusions concerning air quality's effects on mortality can be drawn from these estimates. The expression of air pollution

aggravation effects on mortality in dollar values consistent with the other components of cost-benefit analysis, however, facilitates the efficient allocation of society's scarce resource clean air. By monetizing the mortality component of the marginal social benefit function, more enlightened decisions about the socially optimum level of air quality can be made. Specifically, these dollar estimates will permit decision makers to more closely approximate the optimum level of air quality by permitting the direct comparison of mortality reductions as well as other benefits of air pollution abatement with the costs associated with such abatement policies.

SECTION VII

REFERENCES

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5. Robert Dorfman and Nancy Dorfman, eds., Economics of the Environment (New York: W. W. Norton, 1972), p. XIX.
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8. E. J. Mishan. "A Survey of Welfare Economics, 1939-59," The Economic Journal 70 (June 1960): 206.
9. The marginal rate of substitution in consumption of a for b measures the number of units of b that an individual is willing to sacrifice per unit of a attained so as to maintain a constant level of satisfaction.
10. The marginal rate of transformation in production is the number of units by which the production of b must be decreased in order to expand the output of a by one unit. This ratio is simply equal to the (minus) ratio of the marginal costs of a and b where these costs include both private and social costs.
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12. Adam Smith. The Wealth of Nations. The Modern Library Edition. (New York: Random House, 1965), p. 423.
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41. The inaccuracy of these mortality rates is important to recognize when comparing results.
42. The desirability of using age-sex-race-specific mortality rates is developed in detail on pages 16 and 17.
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44. For an excellent discussion of the limitations involved with using observed total mortality rates for comparisons between populations and the desirability of using standardized rates, see: Shyrock and Siegel, Methods volume 2, pp. 418-424.
45. The difference in age distributions between SMSA's is quite apparent when comparing the Boston SMSA, (population is relatively young) to the Scranton SMSA (population is relatively old).
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50. Recent criticism of these studies has cast sufficient doubt upon their veracity to compel EPA to contract with the National Academy of Science for a reevaluation of the methodology and the conclusions reached by CHES.
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52. It is not expected that all of these independent variables (especially all climatological variables) will be present in the final results.
53. Residence was coded on the death certificates in terms of 1960 census tracts and socioeconomic data was obtained from 1970 census tracts; therefore the census tracts were grouped in order to insure that comparable areas were covered. The resulting groupings were then further aggregated in order to achieve a minimum of 300 deaths per area for the period 1968-1972.

54. Attempts to control for migration with the inclusion of an additional independent variable (i.e., percentage of the population who always lived at present residence) did not improve the overall explanatory power of the model. In fact this variable was seldom significantly different from zero.
55. See, for example, Shryock and Siegel, Methods volume 2, p. 417.
56. The residence on the death certificates was coded on the basis of 1960 census tracts while most other information was coded on the basis of 1970 census tracts. Therefore, groupings of census tracts were formed to make the boundaries consistent.
57. Only 9 percent of the 1970 population of Allegheny County was Negro.
58. While attempts at estimating tobacco expenditures were made using regression analysis, these results were too poor to use for predictive purposes.
59. The Blue Cross estimates were received from personal correspondence with Mr. Dale Colby.
60. This formulation is identical to the crowding variable used by Lave and Seskin, "Air Pollution and Human Health," Science 169 (August 1970): 723-732.
61. The figures for total and residential areas of the individual census tracts were derived from data received from the Southwestern Pennsylvania Regional Planning Commission.
62. For a more detailed description of the interpolation procedures see: Donald S. Shepard, SYMAP Interpolation Characteristics (Cambridge: Graduate School of Design, Harvard University, April 1970).
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64. Alternative functional forms including various air quality interaction terms were tried, although the "best" results were obtained using the weighted linear form. This conclusion is essentially the same reached by Lave and Seskin, "Association Between U.S. Mortality and Air Pollution," p. 288.
65. The main effect of heteroscedasticity, as noted by Teh-wei Hu, Econometrics: An Introductory Analysis (Baltimore: University Park Press, 1973), p. 82, is not the biasness of the estimated regression coefficient but on the efficiency -- the variance of the estimated regression coefficient.

66. Also see: N. Draper and H. Smith, Applied Regression Analysis (New York: John Wiley and Sons, 1966), pp. 77-80.
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68. The choice of the statistically "best" equations were based on the following three criteria: (1) the highest R^2 found to be significant by the corresponding F statistics; (2) regression coefficients that were statistically significant (t test); and (3) a residual pattern which best supported the assumptions that the error terms are independent, have zero mean, and constant variance.
69. As noted by Hu, Econometrics, p. 74, the common case of multicollinearity will cause the standard error of the coefficient to be larger than it is in the case of no collinearity.
70. See Section III, pp. 12-14.
71. See Table III, p. 22 for a listing of which causes of death are being considered pollution related.
72. Two-tailed tests of significance were used for all variables even when a priori sign expectations were met. The reason for this was consistency with those variables for which no a priori sign expectations could be made. One-tailed tests for those variables whose a priori sign expectations were met did not alter the instances in which the variable was not significant.
73. See footnote number 68 above.
74. See Table 1, p. 14.
75. This possibility was investigated by introducing the percent of individuals residing in the tract since 1960 as an independent variable. However, the test proved inconclusive.
76. This statement implies only that labor force participation rates are less for female, rather than indicating a zero female participation rate. The 1970 Allegheny County labor force participation rate of females sixteen and over was 35 percent compared with 75 percent for males.
77. Another policy option is the maintenance of the status quo.
78. A. R. Prest and R. Turvey. "Cost-Benefit Analysis: A Survey," The Economic Journal 75 (December, 1965), p. 686.
79. For a more detailed discussion of the theoretical foundations of cost-benefit analysis, see: D. M. Winch, Analytical Welfare Economics (Baltimore: Penquin, 1971).

80. Winch, Analytical Welfare Economics, p. 135.
81. This definition of consumer's surplus is suggested by J. R. Hicks, Value and Capital, 2nd ed. (London: Oxford University Press, 1968), p. 40.
82. As noted by Winch, Analytical Welfare Economics, p. 139, unless, the elasticity of demand is unitary there will be some transference of expenditures to or from other goods, but with a constant marginal utility of money this is of no consequence.
83. J. R. Hicks. "The Four Consumer's Surpluses," Review of Economic Studies 11 (January 1944), p. 34.
84. Ibid., pp. 34-35.
85. This result can be verified by reviewing Hicks original algebraic formulations, Ibid., p. 37.
86. For a proof of this statement see Winch, Analytical Welfare Economics, p. 142.
87. The arguments are essentially the same as those developed by Winch, Ibid.
88. See, for example, Ibid.
89. For an excellent discussion of the issues surrounding the compensation principle, see Mishan, "A Survey of Welfare Economics."
90. Although these curves resemble production-possibility curves, in this figure the axis measures a specific individual's welfare, ordinal utility.
91. I. M. D. Little. A Critique of Welfare Economics. 2nd ed. (London: Oxford University Press, 1957), p. 109.
92. John V. Krutilla. "Welfare Aspects of Benefit-Cost Analysis," Journal of Political Economy (June 1964). Quoted in Robert Spore, "Property Value Differentials as a Measure of the Economic Costs of Air Pollution," p. 16. Ph.D. dissertation, The Pennsylvania State University, 1972. Emphasis added by author.
93. E. J. Mishan. Cost-Benefit Analysis (New York: Praeger, 1973), p. 321. Emphasis added by author.
94. R. H. Haveman and B. A. Weistrod. "The Concept of Benefits in Cost-Benefit Analysis: With Emphasis on Water Pollution Control Activities." In Cost-Benefit Analysis and Water Pollution Policy, pp. 37-66. Edited by Henry M. Peskin and Eugene P. Seskin. (Washington, D.C.: The Urban Institute, 1973), p. 49.

95. Mishan, Cost-Benefit Analysis, p. 316.
96. Prest and Turvey, "Cost-Benefit Analysis," p. 685-686.
97. Krutilla, "Welfare Aspects of Benefit-Cost Analysis," p. 226.
98. See, pp. 39-44.
99. This formulation is identical to $EACSA = MSC_A$ since $EACSA$ represents a net figure containing both positive and negative consumer surplus'.
100. See, for example, Ronald G. Ridker and J. Henning, "The Determinants of Residential Property Values with Special Reference to Air Pollution," Review of Economics and Statistics 49 (May 1967): 246-257.
101. Ronald G. Ridker. Economic Costs of Air Pollution: Studies in Measurement (New York: Praeger, 1967), p. 25.
102. See, for example, Lave and Seskin "Air Pollution and Human Health."
103. See, for example, R. C. Fink, F. H. Buttner, and W. K. Boyd. Technical Economic Evaluation of Air Pollution Corrosion Costs in Metals in the United States (Columbus: Battelle-Columbus Laboratories, 1971).
104. See, for example, H. Benedict, C. Miller, and R. Olson. Economic Impact of Air Pollution on Plants in the United States (New York: Coordinating Research Council, 1971).
105. For an excellent discussion of various studies, see: Thomas E. Wadell, The Economic Damages of Air Pollution, U.S. Environmental Protection Agencies Socioeconomic Environmental Studies Series (Washington, D. C.: U. S. Government Printing Office, 1974).
106. This statement is verified in detail later in Section VI, pp. 51-54.
107. This type of classification is suggested by Mishan, Cost-Benefit Analysis, pp. 153-155.
108. This method was used by Lave and Seskin, "Air Pollution and Human Health."
109. This estimate was "refined" to include the market value of housewives' services by Burton A. Weisbrod, Economics of Public Health (Philadelphia: University of Pennsylvania Press, 1961).
110. T. C. Schelling. "The Life You Save May Be Your Own." In Problems in Public Expenditure Analysis, pp. 127-176. Edited by Samuel B. Chase. (Washington D.C.: The Brookings Institution, 1968), pp. 149-150. Emphasis added by author.

111. This method was originally formulated to determine the amount of life insurance an individual should purchase. See: Louis I. Dublin and Alfred J. Lotka, The Money Value of a Man (New York: Ronald Press, 1946).
112. E. J. Mishan. "Evaluation of Life and Limb: A Theoretical Approach," Journal of Political Economy 79 (July/August 1971), p. 157.
113. Dan Usher. "An Imputation to the Measure of Economic Growth for Changes in Life Expectancy." In The Measurement of Economic and Social Performance, pp. 193-232. Edited by Milton Moss (New York: National Bureau of Economic Research, 1973), p. 210.
114. For a rigorous mathematical treatment of this derivation, see: Michael Jones-Lee, "The Value of Changes in the Probability of Death or Injury," Journal of Political Economy 82 (July/August, 1974): 549-552.
115. This is not to imply that this value is large relative to the others considered. It may in fact be negative for a perpetual criminal.
116. Richard Zeckhauser. "Procedure for Valuing Lives," Public Policy 23 (Fall, 1975), p. 444.
117. Ibid., p. 436.
118. It is for this reason that Schelling, "The Life You Save," makes the distinction between a "statistical" death and an "individual" death. The current analysis is concerned only with the "statistical" death (i.e., the death of an unknown individual).
119. Mishan, "Evaluation of Life and Limb," p. 174.
120. J. Hirshleifer, T. Bergstrom, and E. Rapport. Applying Cost-Benefit Concepts to Projects which Alter Human Mortality (Los Angeles: School of Engineering and Applied Science, U.C.L.A., 1974), p. 23.
121. See Table 6, p. 30.
122. Richard Thaler and Sherwin Rosen. "The Value of Saving a Life: Evidence from the Labor Market." Paper Presented at the National Bureau of Economic Research Conference on Income and Wealth, Household Production and Consumption, Washington, D. C., November 30, 1973, p. 32.
123. Ibid.
124. All dollar values are in 1967 dollars.
125. Thaler and Rosen, "The Value of Saving a Life," p. 36.

SECTION VIII

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